GEOPHYSICAL SURVEYS FOR CHARACTERIZING THE HYDROGEOLOGIC REGIME IN THE VICINITY OF KEALAKEHE, HAWAII

GEOPHYSICAL SURVEYS FOR CHARACTERIZING THE HYDROGEOLOGIC REGIME IN THE VICINITY OF KEALAKEHE, HAWAII

Prepared For:

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(BGI Project #91025)

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1.0 INTRODUCTION

This report contains a compilation of results of time domain electromagnetic (TDEM) geophysical surveys conducted to assist in ground water resource evaluation in the vicinity of Kealakehe, Island of Hawaii. The surveys were performed by Blackhawk Geosciences, Inc. (BGI) for three separate clients. The clients and the dates for each survey are as follows

- Queen Liliuokalani Trust (QLT) from April 26 to April 30, 1991
- State of Hawaii (State) through Belt Collins and Associates from May 1 to May 2, 1991
- Lanihau Partners (LP) from September 11 to September 13, 1990.

The LP data has previously been interpreted and the results are contained in a separate report delivered to LP in October 1990. By agreement from all concerned parties, the results for all three data sets are contained in this report.

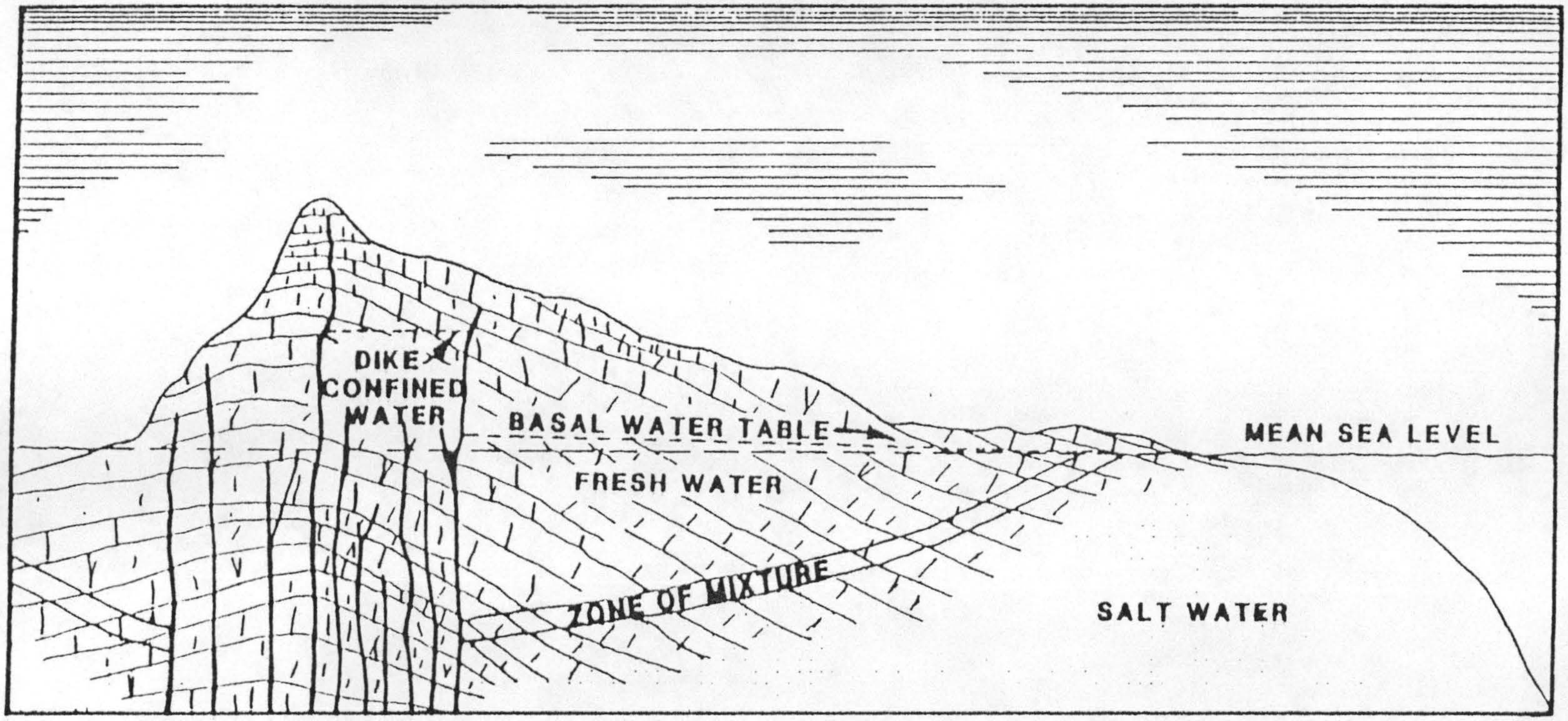
The primary objective of the geophysical surveys was to determine the elevation and thickness of the lens of fresh water floating on salt water. The basis for geophysical surveys for ground water evaluations on volcanic islands can be explained with the use of a hydrogeologic cross-section shown in Figure 1-1. The volcanic rocks are generally permeable and this allows rainwater to percolate directly downward through the island mass. The fresh water in these island settings is generally found in two occurrences:

1. Basal fresh water. The high permeability of the volcanic rocks allows sea water to enter freely under the island, and a balance is reached where a lens of fresh water floats on sea water. In cases of hydrostatic equilibrium, the Ghyben-Herzberg principle states that for every foot of fresh water head above sea level there will be 40 ft of fresh water below sea level.

2. Dike-confined waters. Typically, above a rift zone intrusive dikes originating from a magma source below can form ground water dams, and behind these natural dams significant quantities of ground water can be stored.

Because the electrical resistivity of rock formations is highly dependent upon the salinity of ground water, electrical surface geophysical techniques can map the depth to salt water, and the thickness of the fresh water lens can then be estimated using the Ghyben-Herzberg principle. The impetus for using geophysics is that the cost of a geophysical sounding is about one-thousandth the cost of completing a well at elevations above 1,000 ft.

The specific geophysical method employed was TDEM soundings. This method was selected because it has been proven effective in prior surveys in similar situations in Hawaii.



BLACKHAWK GEOSCIENCES, INC.

SCHEMATIC HYDRO-GEOLOGIC CROSS SECTION

KEALAKEHE AREA
ISLAND OF HAWAII

PROJECT NO: 91022, 91025

Figure 1-1

2.0 LOGISTICS AND DATA ACQUISITION PROCEDURES

2.1 GENERAL

The TDEM surveys were accomplished by a four man crew consisting of two BGI personnel and two local temporary field helpers. The locations of TDEM measurements were determined from consultation with personnel concerned with each property site and their consulting hydrogeologist. During the surveys, TDEM soundings were made along roughly east-west lines traversing each property. Six soundings were acquired on the QLT property, two soundings were made for the State near the Honokohau exploratory well and six soundings were taken for LP near Palani Junction. The location of the soundings for each of the three surveys are shown in Figure 2-1.

Sounding locations were surveyed using a compass and hip chain from known landmarks (i.e., road junctions, rock walls) located on the field maps. Transmitter loop sizes varied from 1,500 ft by 1,500 ft to 200 ft by 200 ft, depending upon elevation. Sounding center elevations were measured with an altimeter in the field and checked with USGS maps. The locations of the soundings were somewhat constrained by land access restrictions for the QLT and State surveys. In addition, sounding locations were also positioned to avoid cultural features (pipelines, power lines, houses, etc.) which deteriorate TDEM data quality.

A daily log of field activities for all three surveys is given in Table 2-1.

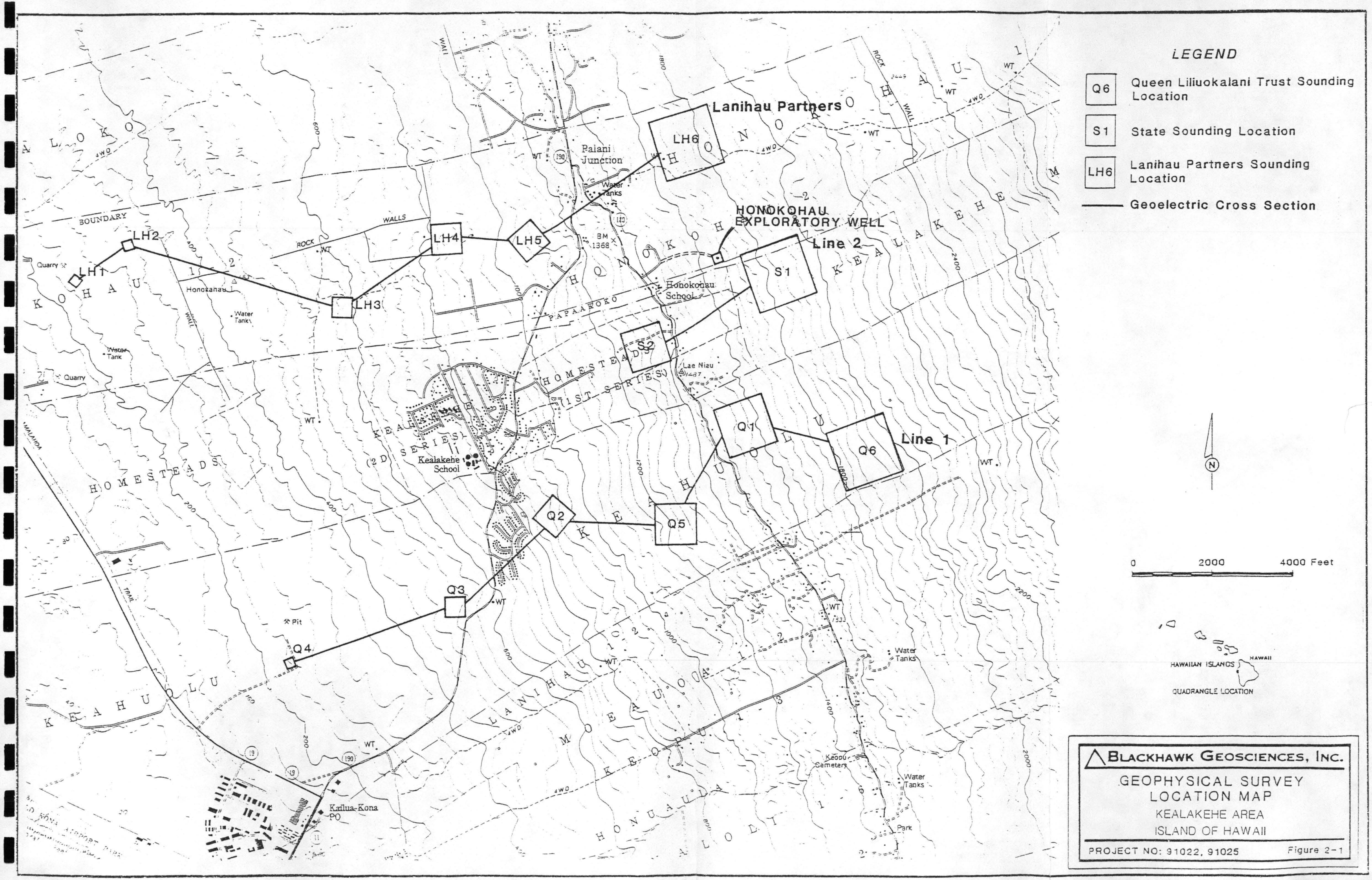
2.2 PROCEDURES

The Geonics EM-37 TDEM system was utilized on this survey. The system basically consists of a transmitter and a receiver. The transmitter loop is constructed of 10 to 12 gauge insulated copper wire. The wire is laid on the ground surface in a square loop varying in size, depending upon the required depth of investigation (larger loop sizes for deeper measurement). A transmitter and motor generator are connected into the non-grounded loop at one corner. A time-varying current is pulsed through the wire at two different base frequencies. The TDEM receiver measures and records the decay of the vertical magnetic field through a receiver coil placed at the center of the non-grounded transmitter loop. Receiver coils with effective areas of 100 m^2 and 1,000 m^2 were utilized at base frequencies of 3 Hz and 30 Hz. During data acquisition numerous transient decays are collected with the receiver for each sounding. Readings were acquired at several receiver gains with opposite receiver polarities for each sounding location. The readings were stored in a DAS-54 solid state data logger, and were nightly transferred to a personal computer for processing. A technical note is given in Appendix A which describes and illustrates the principles of TDEM.

Table 2-1. Daily log of field activities

Date (1990)	Activity
September 6	Mobilization from Denver, CO to Kailua-Kona, HI in conjunction with other surveys.
September 11	Meet with personnel from Lanihau Partners and their consultant. Reconnaissance of Honokohau Property for sounding sites. Take data on soundings LH1, LH2 and LH3.
September 12	Honokohau Property soundings LH4 and LH5.
September 13	Honokohau Property sounding LH6. One-half day of field work.
September 19	Demobilize equipment and BGI personnel.
	(September 7 through 10, and September 14 through 18 were field work at other Hawaii locations)

Date (1991)	Activity
April 22	Mobilize from Denver, CO to Kailua-Kona, HI in conjunction with other surveys.
April 26	Data taken on sounding Q1 for QLT.
April 27	Data taken on sounding Q2 for QLT.
April 28	Data taken on soundings Q3 and Q4 for QLT.
April 29	Data taken on sounding Q5 for QLT.
April 30	Data taken on sounding Q6 for QLT.
May 1	Data taken on sounding S1 for State near Honokohau Exploratory Well.
May 2	Data taken on sounding S2 for State.
May 7	Demobilize equipment and BGI personnel.
	(April 23 through 25, and May 3 through 6, were field work on other Hawaii jobs).


LEGEND
Q6 Queen Liliuokalani Trust Sounding Location
S1 State Sounding Location
LH6 Lanihau Partners Sounding Location
Geoelectric Cross Section
Lanihau Partners
LH1
LH2
LH3
LH4
LH5
LH6
HONOKOHAU EXPLORATORY WELL
Line 2
S1
S2
Q7
Q6
Line 1
Q2
Q5
Q3
Q4
Palani Junction
Water Tanks
Honokohau School
Lae Niau
Kealakehe School
Kailua-Kona PO
Kaoou Cemetery
Park
Honokanau
Quarry
Pit
BOUNDARY
ROCK WALLS
PAPAAKOKO
HOMESTEADS (1ST SERIES)
KEALAKEHE (2D SERIES)
HOMESTEADS
LANIHAU 1-2
0 2000 4000 Feet
HAWAIIAN ISLANDS
HAWAII
QUADRANGLE LOCATION
BLACKHAWK GEOSCIENCES, INC.
GEOPHYSICAL SURVEY LOCATION MAP
KEALAKEHE AREA
ISLAND OF HAWAII
PROJECT NO: 91022, 91025
Figure 2-1

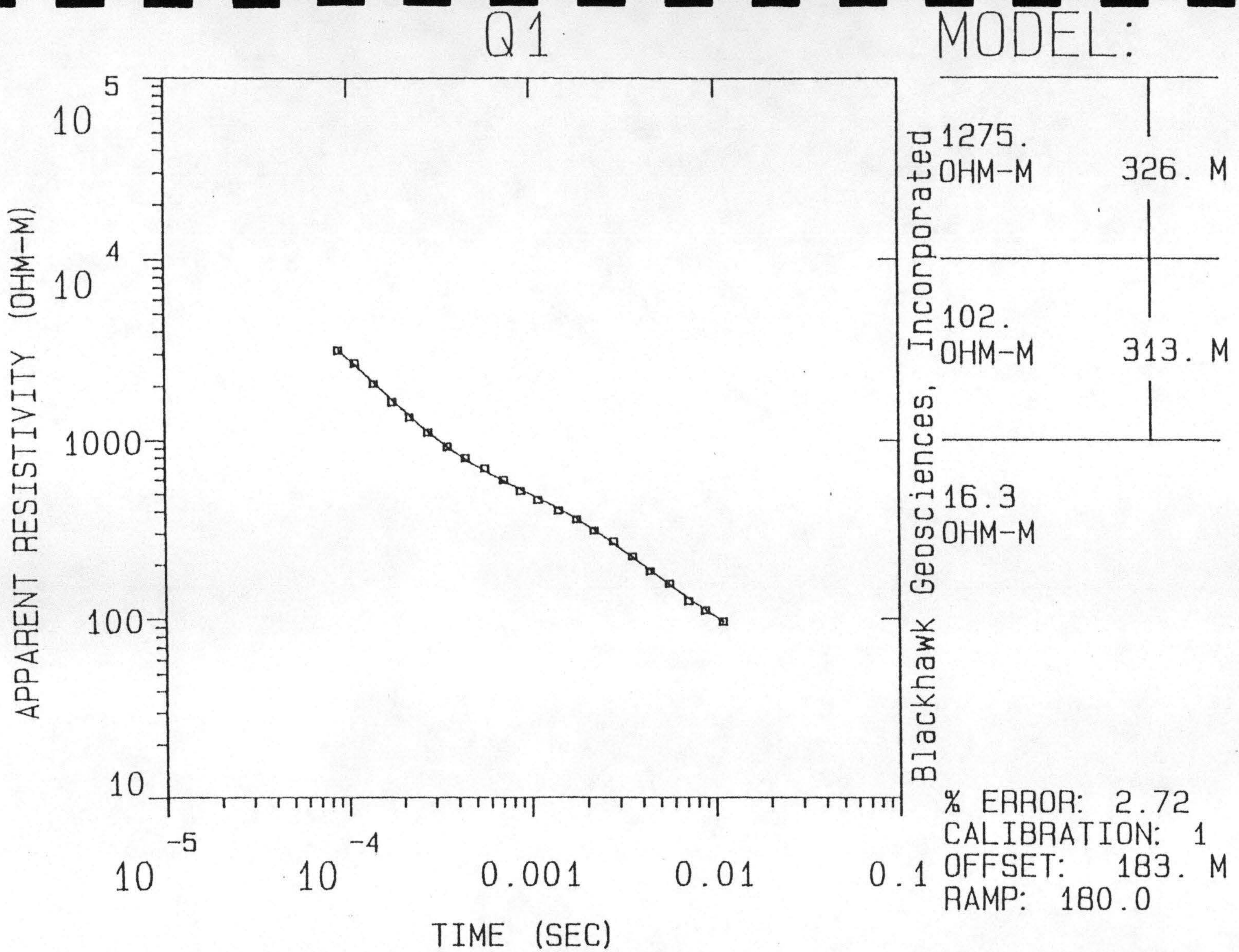
3.0 DATA PROCESSING

The field data acquired each day was transferred from the DAS-54 data logger to a personal computer. The data for each sounding location is edited and combined (both 3 Hz and 30 Hz frequencies) to produce a transient decay curve. This decay curve is transformed into an apparent resistivity curve, which is entered into an Automatic Ridge Regression Transient Inversion Program (ARRTI). From the apparent resistivity curve a one-dimensional model of resistivities and thicknesses is calculated.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers, and the resistivities and thicknesses of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data set. The inversion program does not change the total number of layers within the model, but allows all other parameters to float freely.

An example data set is given in Figures 3-1 and 3-2 for sounding Q1. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed behavior of the true resistivity layering model shown on the right. Figure 3-2 is the inversion table and it lists in column 4 the error between measured and computed data in each time gate.

The apparent resistivity curves and data sheets for all three of the surveys (QLT, State and LP) are contained in Appendix B.



BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET

KEALAKEHE AREA
ISLAND OF HAWAII

PROJECT NO: 91022, 91025

Figure 3-1

Q1

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		475.5	1560.0		
1274.99	325.8	149.7	491.3	0.3	0.3
102.11	313.0	-163.3	-535.7	3.1	3.3
16.33					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	3.13E+03	3.14E+03	-0.554	
2	1.10E-04	2.66E+03	2.60E+03	2.499	
3	1.40E-04	2.05E+03	2.07E+03	-1.103	
4	1.77E-04	1.63E+03	1.66E+03	-2.067	
5	2.20E-04	1.34E+03	1.36E+03	-1.703	
6	2.80E-04	1.10E+03	1.10E+03	-0.110	
7	3.55E-04	9.21E+02	9.12E+02	0.937	
8	4.43E-04	7.93E+02	7.77E+02	1.955	
9	5.64E-04	6.91E+02	6.67E+02	3.520	
10	7.13E-04	5.94E+02	5.86E+02	1.495	
11	8.81E-04	5.18E+02	5.26E+02	-1.569	
12	1.10E-03	4.61E+02	4.72E+02	-2.369	
13	1.41E-03	4.04E+02	4.13E+02	-2.180	
14	1.77E-03	3.60E+02	3.61E+02	-0.294	
15	2.20E-03	3.11E+02	3.13E+02	-0.431	
16	2.80E-03	2.70E+02	2.63E+02	2.876	
17	3.55E-03	2.23E+02	2.19E+02	1.477	
18	4.43E-03	1.83E+02	1.85E+02	-0.788	
19	5.64E-03	1.56E+02	1.54E+02	1.387	
20	7.13E-03	1.25E+02	1.29E+02	-3.159	
21	8.81E-03	1.11E+02	1.11E+02	-0.046	
22	1.10E-02	9.62E+01	9.58E+01	0.394	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 180.0 MICROSEC, DATA: Q1
2614 002N 001E Z OPR XTL H 6 8+100
Ch.21 = 0.18 Ch.22 = 0.089 Ch.23 = 14.5 Ch.24 =
RMS LOG ERROR: 1.16E-02, ANTILOG YIELDS 2.7175 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.32				
P 2	-0.17	0.51			
P 3	0.00	-0.11	0.13		
T 1	0.15	0.15	0.00	0.91	
T 2	-0.11	-0.07	0.08	0.05	0.77
	P 1	P 2	P 3	T 1	T 2

BLACKHAWK GEOSCIENCES, INC.

EXAMPLE DATA SET

KEALAKEHE AREA
ISLAND OF HAWAII

PROJECT NO: 91022, 91025

Figure 3-2

4.0 INTERPRETATION RESULTS

4.1 GENERAL

The results of the interpretation of individual soundings is the resistivity layering as a function of depth. In cases where measurements are taken relatively close together, the results of the individual measurements can be linked together to produce a geoelectric cross section along a line. From the six soundings acquired across the QLT property, one geoelectric cross section was constructed. Using the two soundings taken near the Honokohau Exploratory Well a second geoelectric cross section was made. A third cross section was made from the six soundings taken on the LP property. Figure 2-1 shows the individual TDEM sounding locations and the three west to east geoelectric cross sections.

From many prior geophysical surveys over volcanic rocks of Hawaii, including geologic and geohydrologic information, characteristic ranges of resistivities can be assigned to known geologic and geohydrologic units. The assigned resistivity ranges for the various units expected to be encountered in the survey areas are shown in Figure 4-1. As is shown in the figure, an overlap occurs between the resistivity ranges. The most extensive overlap occurs between the ash flows, weathered volcanics or intrusives, and the dry unweathered or fresh-brackish water saturated volcanics. In most situations these units can be separated by their individual resistivity value in ohm-m and their relative depth of occurrence in the geoelectric cross section.

Where a very low resistivity layer (< 5 ohm-m) is detected below sea level in the TDEM interpretation, this layer is expected to be caused by salt water saturated volcanics. Static water levels (heads) can subsequently be calculated from these soundings by using the Ghyben-Herzberg principle. This principle states that under conditions of static equilibrium, for every foot of fresh water above sea level there will be about forty feet of fresh water below sea level. An illustration of the Ghyben-Herzberg principle is given in Figure 4-2. This principle, however, assumes static equilibrium and may not apply to TDEM sounding data in close proximity to ground water damming structures (i.e., dikes, rifts, etc.).

TDEM soundings in areas where ground water has been shown to be dike confined typically show high resistivity layers (greater than 100 ohm-m) to the exploration depth of the TDEM system (typically well below sea level). In other words, no sea water saturated formations are indicated within the entire section.

Within the structure controlled area which separates the basal mode and dike confined areas, TDEM data often exhibit intermediate resistivity values (10 to 100 ohm-m) that may occur both above and below sea level. The data taken in these areas is expected to be distorted or influenced by the structures and may not be diagnostic of true resistivity layering. This is due to the current limitation of 1-D interpretations for TDEM data. From TDEM data in these areas, it is generally not possible to determine the exact origin and nature of the subsurface conditions influencing the formation resistivities.

4.2 GEOELECTRIC CROSS SECTIONS

Line 1 - Queen Liliuokalani Trust (QLT)

Figure 4-3 shows the results of six TDEM soundings acquired over the QLT property. They are presented as a west to east trending geoelectric cross section, in which units that display similar resistivity values have been joined together.

Similar two-layer sequences are interpreted in the geoelectric cross section for soundings Q4, Q3 and Q2. The upper layer of the section exhibits resistivity values ranging from 509 ohm-m to greater than 7,000 ohm-m. This upper layer is interpreted to represent dry unweathered volcanics above sea level, and where it occurs below sea level it is expected to be saturated with fresh-brackish basal mode water. The lower layer of these three soundings exhibits very low resistivity values ranging from 3.3 to 3.6 ohm-m and is interpreted to represent salt water saturated volcanics. The approximate thickness of the fresh-brackish water lens is interpreted to vary from 10 ft below sounding Q4, which is nearest to the shoreline, to 42 ft beneath sounding Q2.

Soundings Q5 and Q1 are in a transition zone between an area where a salt water interface is detected (soundings Q4, Q3 and Q2) and sounding Q6 where salt water was not detected. Beneath soundings Q5 and Q1 resistivity values are influenced by lateral discontinuities, and intermediate resistivity values are observed. The 52 ohm-m to 102 ohm-m resistivity values observed to occur above sea level may not represent the true formation resistivity beneath soundings Q5 and Q1. This transition zone may have several possible geologic causes, such as ash flows, weathered volcanics or intrusives (i.e., dikes).

Beneath sounding Q6 a layer with a resistivity of less than 5 ohm-m was not observed within the effective exploration depth of about 500 ft below msl. The lowest resistivity measured was about 429 ohm-m, and below sea level this value would be characteristic of fresh water saturated volcanics. Since the salt water interface was not detected below this sounding, the elevation of the water table cannot be estimated. From the geoelectric cross section, the exact location of the hydrogeologic boundary is difficult to determine, but assuming that the ground water flow is from east to west, geophysical and hydrogeologic information would place the boundary between soundings Q1 and Q6.

Line 2 - State of Hawaii (State)

The geoelectric cross section for line 2 in the vicinity of the Honokohau Exploratory Well is shown in Figure 4-4. Sounding S2 shows a two-layer sequence where the lower layer exhibits an intermediate resistivity (11 ohm-m) which occurs above sea level. This sounding appears to be located in a transition zone where lateral changes are interpreted to be effecting the resistivity values. An attempt to acquire a sounding downslope from S2 to locate basal mode water was unsuccessful because of property access restrictions. Therefore, the west boundary of the interpreted geologic structure is undetermined.

Sounding S1 was located approximately 1,500 ft upslope and east of the Honokohau Exploratory Well. Drilling results from the well disclosed a high static water level of 110 ft above msl in the well (personal communication, Tom Nance, May 1991). A layer with a resistivity of less than 5 ohm-m was not observed below sounding S1 within the effective exploration depth of the measurement (about -500 ft elevation). The lowest resistivity measured in this three-layer sequence was 186 ohm-m. This resistivity value is shown to occur above and below sea level, and below sea level this would be characteristic of fresh water saturated volcanics. The lower layer of this three-layer sequence exhibits a resistivity of 936 ohm-m. Since the salt water interface was not detected beneath sounding S1, an estimate of the water table cannot be made. A sharp resistivity transition occurs between soundings S2 and S1 and a hydrogeologic structure is inferred in the cross section.

Lanihau Partners (LP)

Figure 4-5 shows the geoelectric cross section from the LP 1990 survey. Within the cross section, soundings LH1 through LH4 show similar two-layer sequences with a thin lens of fresh-brackish basal mode water interpreted to occur beneath these four soundings. The approximate thickness of the fresh-brackish water lens is expected to vary from 17 ft at station LH2 to 62 ft at station LH4.

Sounding LH5 is in a transition zone between an area where the salt water interface was detected (soundings LH1 through LH4) and where it was not detected (sounding LH6). Where the transition zone occurs an intermediate resistivity value occurs (12 ohm-m), this value is expected to be influenced by lateral changes in the section. The lateral changes may be caused by several geologic features, such as ash flows or intrusives. A hydrogeologic boundary is interpreted to occur between soundings LH4 and LH6, and assuming ground water flow is from LH6 towards LH5, hydrogeologic considerations would place the boundary between these two soundings.

4.3 HYDROGEOLOGIC INTERPRETATIONS

Table 4-1 lists the approximate thickness of the fresh-brackish water lens calculated from the elevation of the salt water interface interpreted from the individual TDEM soundings. The table does not include the value of head calculated by using the Ghyben-Herzberg principle. The list includes the six QLT soundings, two State soundings, and the six LH 1990 survey soundings taken on the Honokohau property.

Table 4-1. **Hydrogeologic information derived from TDEM soundings**

Sounding No. (Year)	Surface Elevation (ft)	Approximate Thickness of Fresh-Brackish Water Lens (ft)
Q1 (1991)	1560	Transition zone
Q2 (1991)	880	42
Q3 (1991)	510	14
Q4 (1991)	240	10
Q5 (1991)	1220	Transition zone
Q6 (1991)	1920	Structure Controlled
S1 (1991)	1840	Structure Controlled
S2 (1991)	1300	Transition zone
LH1 (1990)	250	55
LH2 (1990)	320	17
LH3 (1990)	575	45
LH4 (1990)	865	62
LH5 (1990)	1070	Transition zone
LH6 (1990)	1720	Structure Controlled

This information is further summarized on the interpretation map shown in Figure 4-6. The soundings are classified into three main groups:

(1) Beneath seven of the TDEM soundings (below the 1,000 ft elevation level) a layer of low resistivity less than 5 ohm-m was detected. A fresh-brackish water resource is interpreted to exist in the basal mode for these seven soundings. The approximate thickness of the lens floating on salt water was found to be thin and vary from 10 ft at sounding Q4 to 62 ft at sounding LH4.

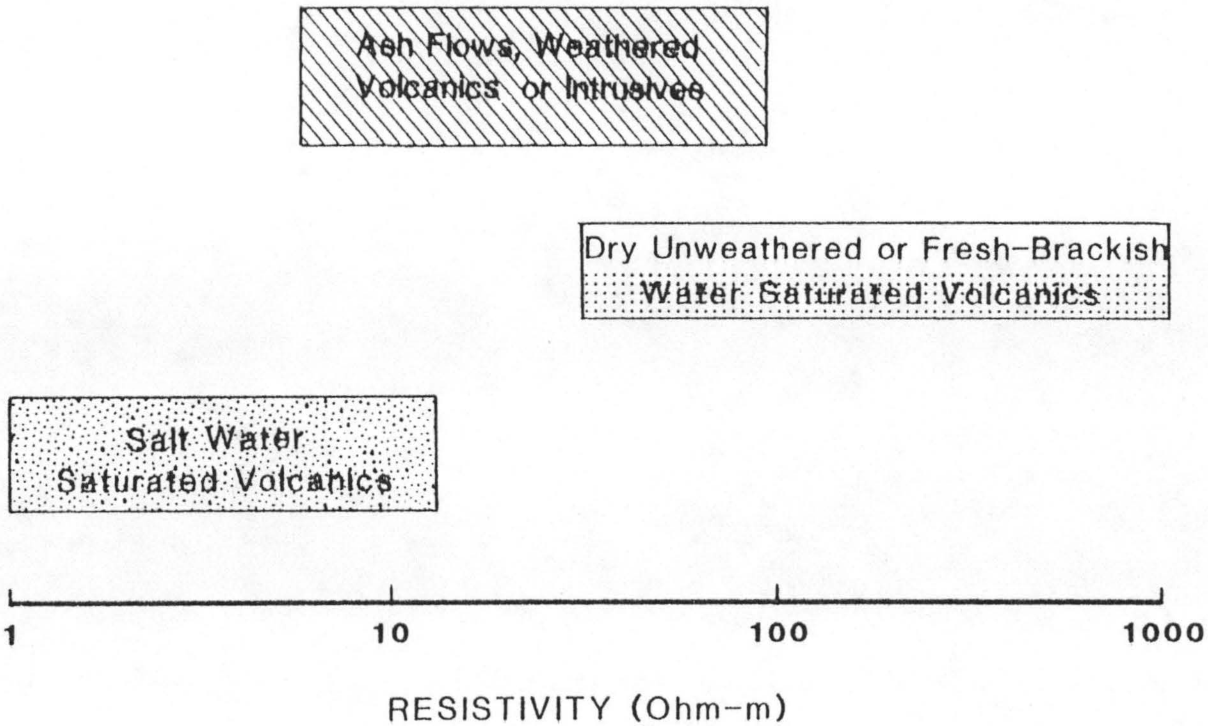
(2) A group of soundings in which resistivities are influenced by lateral discontinuities and ground water damming structures or formations are inferred. Intermediate resistivity values occurring both above and below sea level are common this area.

(3) A group of soundings in which high resistivity values are detected to the exploration depth of the TDEM system (east of blue line in Fig. 4-6). In this area ground water occurrences are expected to be controlled by the damming structures and high level water may be present. The Honokohau Exploratory Well, in which a head of 110 ft above msl was discovered, is located in this area.

Several features stand out on the interpretation map:

(1) An area above the 1,000 ft elevation level, in which resistivity values are interpreted to be influenced by lateral discontinuities. The trend of this lower boundary of the transition zone is approximately parallel to the 1,000 ft contour line.

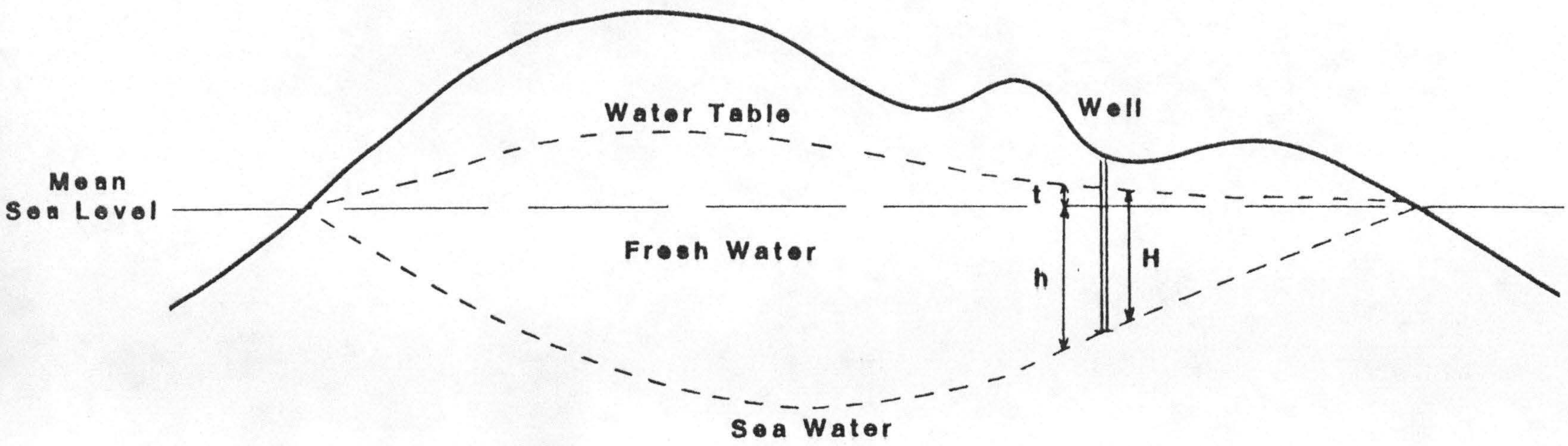
(2) The upper boundary between the transition zone and structure controlled water (heavy blue line) changes in elevation from approximately 1,720 ft near line 1 in the south, to 1,400 ft near the LP line to the north. The bearing of this upper boundary is $N50^0W$ towards Palani Junction.



BLACKHAWK GEOSCIENCES, INC.

CHARACTERISTIC RESISTIVITY RANGES
KEALAKEHE AREA
ISLAND OF HAWAII

PROJECT NO: 91022, 91025 Figure 4-1



t = 1/40 (h)

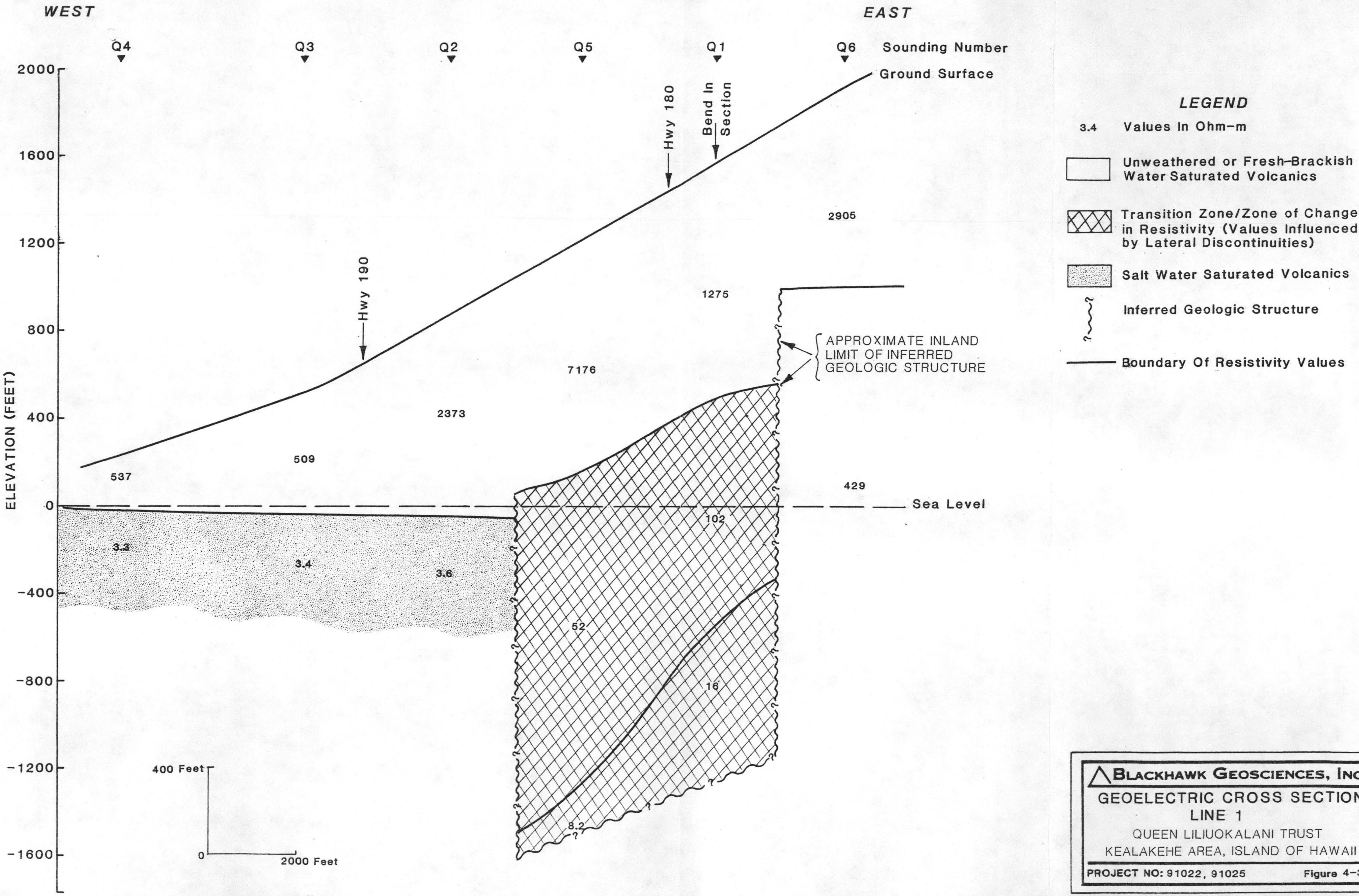
FROM: HERZBERG

BLACKHAWK GEOSCIENCES, INC.

Illustration of the
Ghyben-Herzberg Principle
KEALAKEHE AREA
ISLAND OF HAWAII

PROJECT NO: 91022, 91025

Figure 4-2

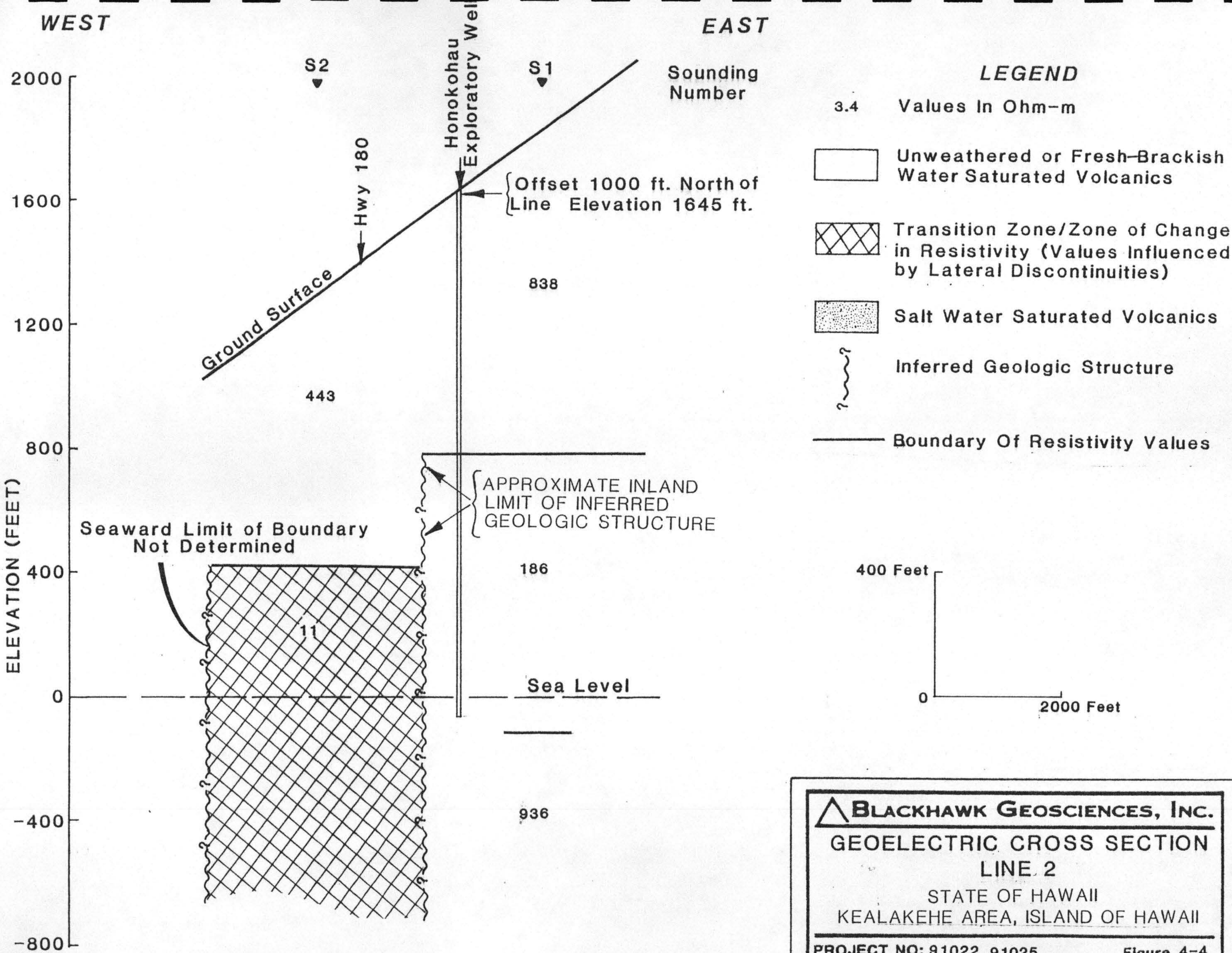


BLACKHAWK GEOSCIENCES, INC.

GEOELECTRIC CROSS SECTION LINE 1

QUEEN LILIUOKALANI TRUST
KEALAKEHE AREA, ISLAND OF HAWAII

PROJECT NO: 91022, 91025 Figure 4-3



BLACKHAWK GEOSCIENCES, INC.

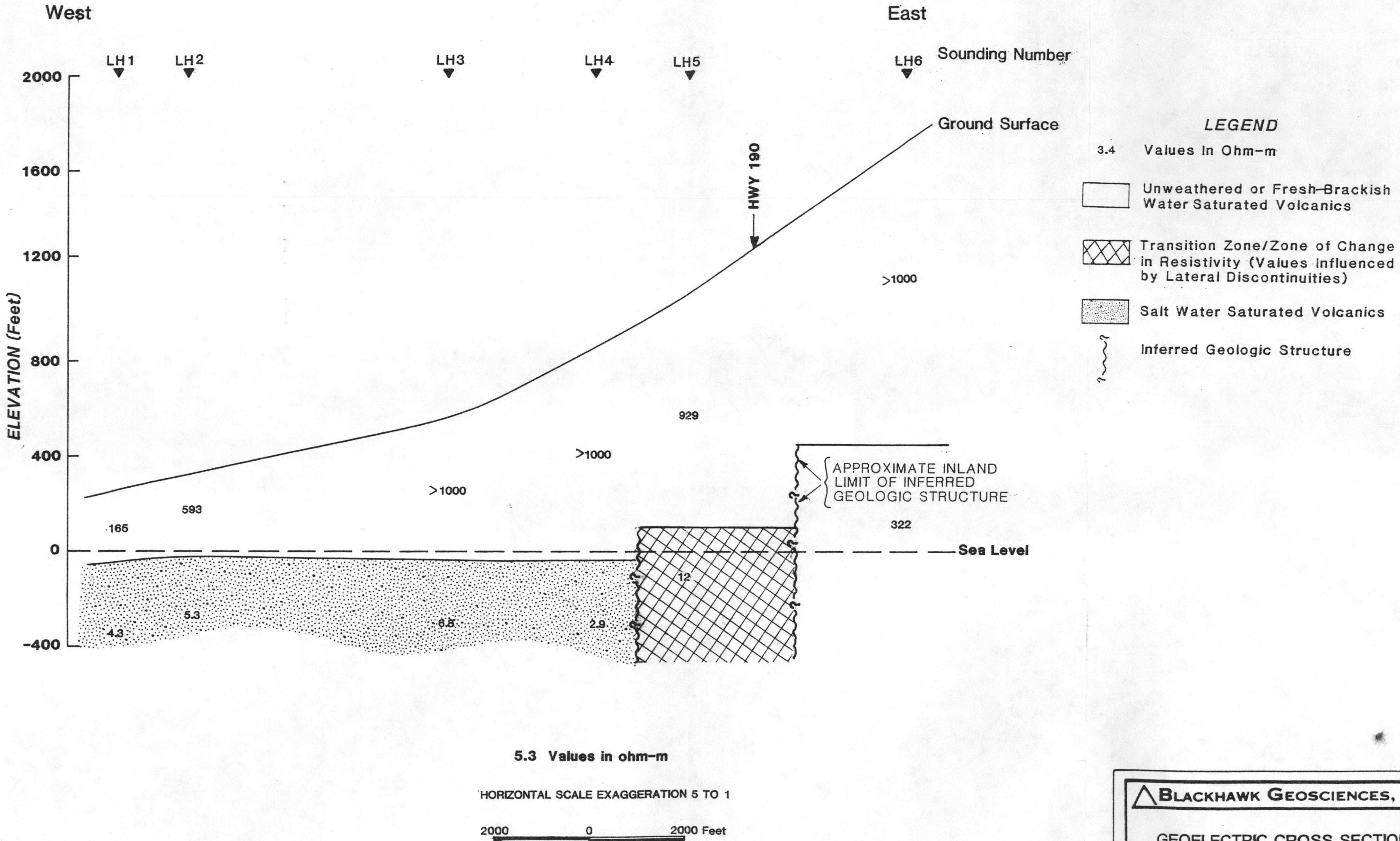
GEOELECTRIC CROSS SECTION LINE 2

STATE OF HAWAII

KEALAKEHE AREA, ISLAND OF HAWAII

PROJECT NO: 91022, 91025

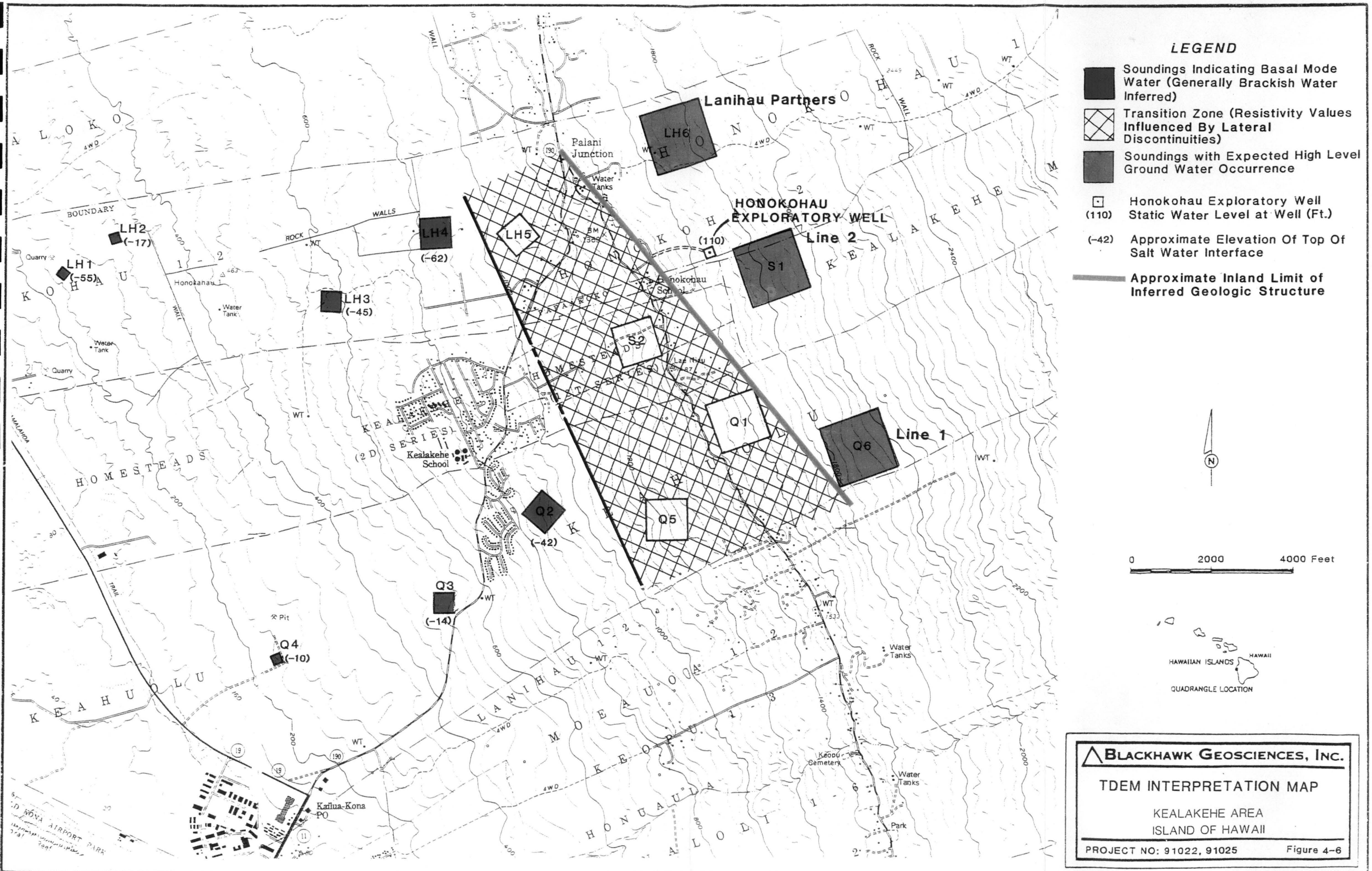
Figure 4-4



BLACKHAWK GEOSCIENCES, INC.

GEOELECTRIC CROSS SECTION
LANIHAU PARTNERS L.P.
KEALAKEHE AREA, ISLAND OF HAWAII

PROJECT NO: 91022, 91025 Figure 4-5



LEGEND
Soundings Indicating Basal Mode Water (Generally Brackish Water Inferred)
Transition Zone (Resistivity Values Influenced By Lateral Discontinuities)
Soundings with Expected High Level Ground Water Occurrence
Honokohau Exploratory Well
(110) Static Water Level at Well (Ft.)
(-42) Approximate Elevation Of Top Of Salt Water Interface
Approximate Inland Limit of Inferred Geologic Structure
Lanihau Partners
HONOKOHAU EXPLORATORY WELL
(110)
Line 2
Line 1
LH1 (-55)
LH2 (-17)
LH3 (-45)
LH4 (-62)
LH5
LH6
S1
S2
Q1
Q2 (-42)
Q3 (-14)
Q4 (-10)
Q5
Q6
Palani Junction
Water Tanks
Honokohau School
Kealakehe School
Kailua-Kona PO
Keopu Cemetery
Park
Quarry
Pit
0 2000 4000 Feet
HAWAIIAN ISLANDS
HAWAII
QUADRANGLE LOCATION
BLACKHAWK GEOSCIENCES, INC.
TDEM INTERPRETATION MAP
KEALAKEHE AREA
ISLAND OF HAWAII
PROJECT NO: 91022, 91025
Figure 4-6

5.0 CONCLUSIONS AND RECOMMENDATIONS

The main objective of the TDEM survey was to assist in ground water resource evaluation in the vicinity of Kealakehe, Hawaii. The three data sets from the Queen Liliuokalani Trust, State of Hawaii, and Lanihau Partners are incorporated into this report, and the interpretation results are shown in Figure 4-6. Several distinct areas of hydrogeologic behavior are observed in this compiled data set. These are:

(1) An area approximately below the 1,000 ft elevation level, where ground water is expected to occur in the basal mode. The salt water interface in this area is interpreted to be very close to sea level (-10 to -62 ft; Table 4-1) which indicates a thin basal water resource which is most likely brackish.

(2) A transition zone, between expected basal mode and high level ground water. This area is interpreted to be above the 1,000 ft elevation level, where ground water is expected to be controlled by damming structures and resistivity values are influenced by lateral discontinuities.

(3) An area of structurally controlled ground water (above heavy blue line). The interpreted boundary between the transition zone and structure controlled ground water is located above the 1,400 ft elevation level near the Palani Road Junction and increases in elevation towards the south. The dominant bearing of the boundary is interpreted to be N50^{0}W between the three geoelectric cross sections.

The accuracy in determining the exact location of the boundary of the transition zone from TDEM measurements is influenced by several factors:

(1) Lateral discontinuities effecting the TDEM sounding data, due to subsurface structures causing complex formation resistivities to be exhibited in this zone. The apparent geologic structure (or structures) causing the damming of the ground water flow may actually be narrower than the large transition zone indicated in Figure 4-6. TDEM measurements are effected by lateral changes in the subsurface and this is clearly the case in the transition zone. TDEM soundings cannot determine the cause of these subsurface features.

(2) Distances between TDEM measurements (data density) across the transition zone are in some cases, relatively large (greater than 5,000 ft). To assist in delineating the boundary more accurately, additional

measurements are recommended between soundings through the transition zone and both north and south of existing soundings to map the extent of the feature. If the structure controlled boundary continues to the north at the expected N50^{0}W bearing, a well drilled above the projected boundary to the north and at lower elevation than the Honokohau Well may prove successful.

The accuracy in determining the depth to the salt water saturated interface is estimated to be approximately $\pm$ 5% of the total depth measured.

PRINCIPLES OF TIME DOMAIN EM

BLACKHAWK GEOSCIENCES, INC.

Question.-- What is TDEM?

Answer.-- TDEM is a surface geophysical method for determining the lateral and vertical resistivity variation (geoelectric section) in the subsurface.

Question.-- What useful information can be derived from the geoelectric section?

Answer.-- Electrical resistivity can be used as an indicator for mapping several important objectives in the subsurface, such as:

1. <u>Presence of contaminants</u>. Dissolved solids in ground water decrease formation resistivities, so that industrial contaminant plumes and differences in salinity (e.g., salt water intrusion) can often be delineated from geoelectric sections.

2. <u>Soil and rock types</u>. Clays and clay shales, and formations of low hydraulic permeability, have lower resistivities than formations of high hydraulic permeability, such as sands and gravels, sandstones, basalts, and high porosity limestones. The geoelectric section can, therefore, be used to map continuity of clay and clay shale lenses.

3. <u>Fractures and shear zones</u>. Such zones are conduits for ground water flow and contaminant migration, and they are often characterized by zones of low resistivity. The reasons for the lower resistivities of these zones are infilling of the fracture zones by clay gouge, alteration of wall rock, and higher water contents.

Question.-- What advantages does TDEM have over other electrical and electromagnetic methods, such as resistivity (direct current) and electromagnetic conductivity profiling with the Geonics EM-31 and EM-34?

Answer.-- The advantages of TDEM over other electrical and electromagnetic methods are

- better vertical and lateral resolution

- lower sensitivity to geologic noise (see page 5)

- the ability to explore below highly conductive layers (e.g., brine saturated layers and clay lenses).

Some of the most frequently asked questions about TDEM and their answers are given below.

Question.-- Are the principles of TDEM similar to electromagnetic induction profiling, such as used in the Geonics EM-31 and EM-34?

Answer.-- Yes, the principles of electromagnetic induction profiling in the frequency domain (FDEM), used in the Geonics EM-31 and EM-34, are in many ways similar to the principles of TDEM.

An important difference between FDEM and TDEM is the current waveform driven through the transmitter loops. It is a continuous, harmonic-varying current in FDEM, and a half-duty cycle waveform in TDEM.

Question.-- Why does the current waveform of the transmitter make a large difference?

Answer.-- The large difference results from the fact that in FDEM the secondary magnetic field due to ground currents is measured when the transmitter current is on, and in TDEM when the transmitter current is off. In both cases the time-variant current driven through the transmitter causes a time-variant primary magnetic field. Associated with this primary magnetic field is an induced electromotive force (emf) that causes eddy current flow in the subsurface. The intensity of these currents is used to determine subsurface conductivities. The induced emf is a harmonic-varying function in FDEM and consists of narrow pulses in TDEM.

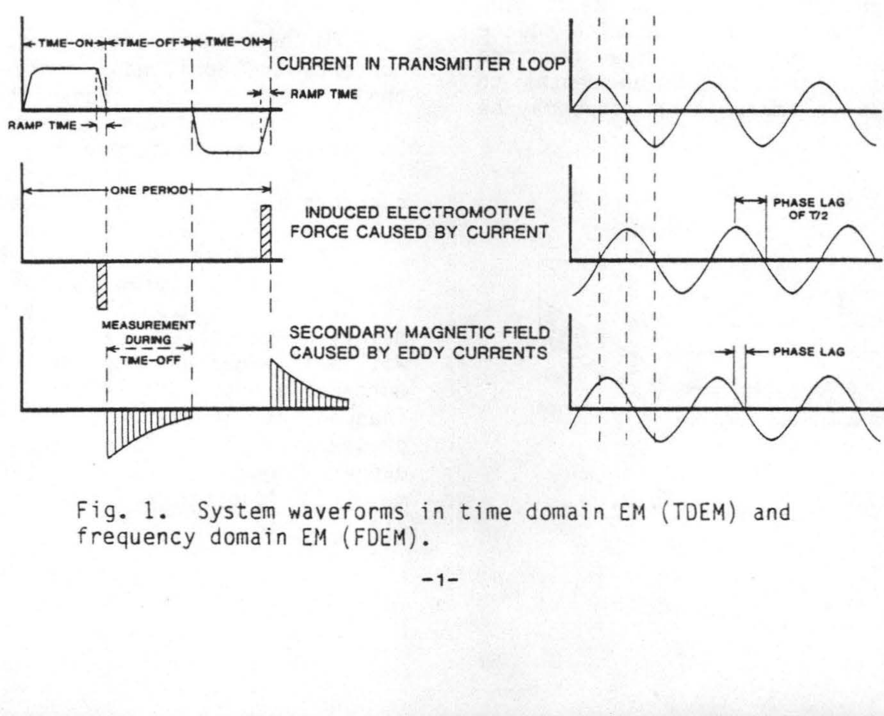


Fig. 1. System waveforms in time domain EM (TDEM) and frequency domain EM (FDEM).

The receiver measures the emf due to the secondary magnetic field of these eddy currents induced in the subsurface, and in the case of FDEM, the emf measured by the receiver is the sum of (1) the primary magnetic field (emf_p due to currents in the transmitter), and (2) the secondary magnetic field (emf_s due to eddy current flow in the ground). Thus,

$$emf_t = emf_p + emf_s$$

where subscript t, p and s refer to total, primary, and secondary magnetic field, respectively. Clearly, emf_s is the only component containing information about the subsurface. Unfortunately, in most situations, the amplitude of emf_s is only one part in 10^4 parts of emf_p. Thus, in FDEM, a small component of emf containing all the useful information about the subsurface must be measured in the presence of a large component containing no information.

In the EM-31 and EM-34 ground conductivity is determined by measuring only the component of emf_s that is in quadrature phase (90^o out-of-phase) with emf_p. Unfortunately, theory shows that the in-phase component is more sensitive to ground conductivity. Measuring only the quadrature phase component limits the accuracy, exploration depth, and utility of FDEM systems.

TDEM improves the situation, because measurements are made during the time the transmitter is off. During off-time the only component of emf measured by the receiver is emf_s. Emf_s is determined in the absence of emf_p, greatly improving its accuracy of measurements.

Question.-- Briefly explain how subsurface resistivities are derived from TDEM measurements.

Answer.-- A TDEM system consists of a transmitter and a receiver. The transmitter configuration often used in ground water and environmental applications is a square loop of insulated wire laid on the ground surface (Figure 2). A multi-turn air coil receiver (about 1 m diam) is placed in the center of the loop. The sizes of the transmitter loops employed are mainly dependent upon the required exploration depth and geoelectric section. Typically, the side of a square is about one-half to two-thirds of the required exploration depth. Thus, for exploration depths to about 200 ft, 75 ft by 75 ft transmitter loops may be employed.

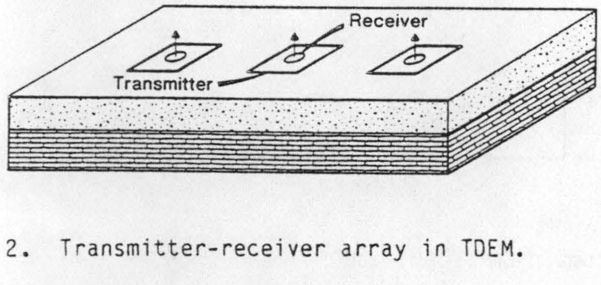


Fig. 2. Transmitter-receiver array in TDEM.

The current waveform driven through the transmitter loops is shown in Figure 1. The waveform consists of equal periods of time-on and time-off. The base frequencies employed in the Geonics instrumentation we employ can be varied from 300 hz, 30 hz, 3 hz and 0.3 hz. These frequencies result in on/off intervals of 0.833, 8.33, 83.3 and 833 msec, respectively.

The current driven through the transmitter loops creates a primary magnetic field. During the rapid current turn-off this primary magnetic field is time-variant and in accordance with Faraday's Law there will be an electromagnetic induction during this time (Figure 1b). This electromagnetic induction in turn results in eddy current flow in the subsurface. The intensity of these currents at a certain time and depth depends on ground conductivity.

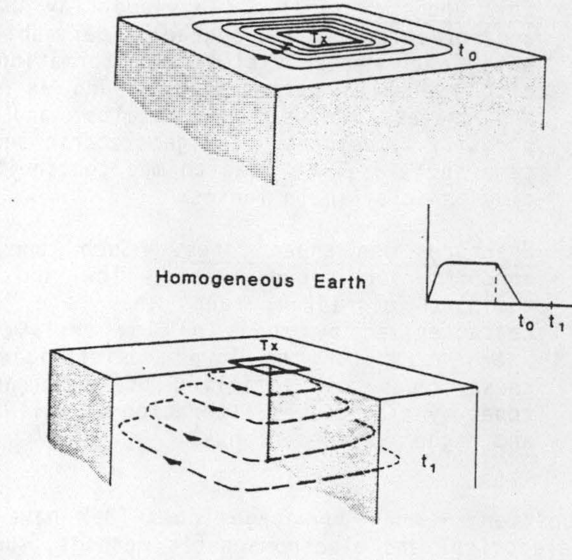


Fig. 3. Current distribution in FDEM at two times after current turn-off.

In near horizontally layered ground, the eddy currents are horizontal closed rings concentric about the center of the transmitter loop. A schematic illustration of these currents is shown in Figure 3. Immediately after turn-off (t_0) the currents are concentrated near the surface, and with increasing time currents are induced at greater depth (t_1).

The receiver measures the emf due the secondary magnetic field caused by these ground eddy currents (Figure 1c). At early time, when the currents are mainly concentrated near the surface, the emf measured will mainly reflect the electrical resistivity of near surface layers. With increasing time, as currents are induced at greater depth, the emf measured will progressively be more influenced by properties of deeper layers. Thus, in TDEM exploration, depth is mainly a function of time of measurement after turn-off.

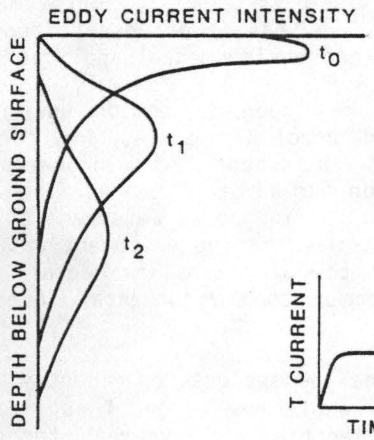


Fig. 4. Schematic illustration of eddy current distribution at different times after turn-off.

Another useful presentation of distribution of current intensity as a function of time is given in Figure 4. At early time, t_0, all currents are concentrated near the surface. At later times (e.g., t_3) the current maxima occur at increasingly greater depth. Thus, from measurements of the decay of emf at one location, the geoelectric section to a substantial depth is obtained.

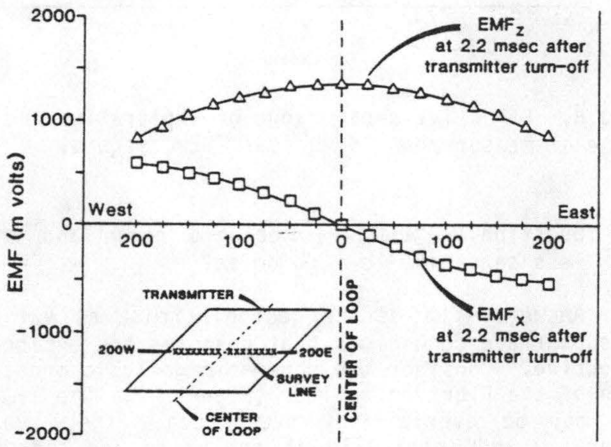


Fig. 5. Spatial behavior of emfs due to vertical (emf_z) and horizontal (emf_x) magnetic field on a profile through the center of square transmitter loop at one time (2.2 millisec) after turn-off.

The emfs caused by square transmitter loops vary with time and distance from the center. Figure 5 shows a typical measured behavior of emfs at a certain time (2.2 milliseconds) after turn-off. At other times the amplitudes will be different, but the spatial behavior is similar. The spatial behavior of the emf_z is relatively flat about the center so that measurements of emf, due to the vertical magnetic field, are relatively insensitive to errors in surveying the center of the loop, or to deviations from a square loop. This is clearly of practical value because it (1, reduces the cost of land surveys and measurement errors, and (2) allows for some flexibility in the field in positioning the measurement stations.

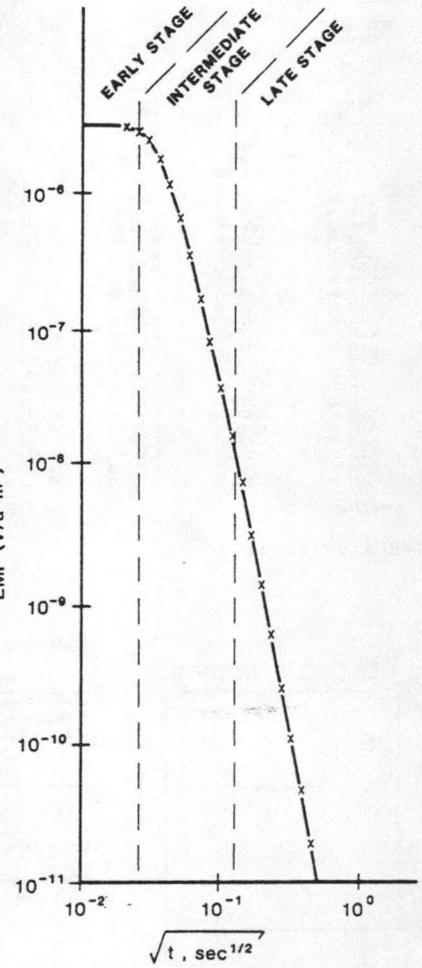


Fig. 6. Typical transient behavior of emf_z in center of square transmitter loop.

Thus, in TDEM soundings, the geoelectric section is derived from measurement of the emf due to the vertical magnetic field (emf_z) as a function of time during the period the transmitter is off. Figure 6 shows a typical behavior of emf_z as a function of time. Emf_z can be seen to decay rapidly with increasing time. One transient decay recorded over a few tens of milliseconds contains information about resistivity layering over a significant depth range.

The emfs, due to the decay of the ground eddy currents, must be measured in the presence of ambient noise sources, such as geomagnetic storms, lightning, 60 hertz powerlines, and other man-made sources. It is common to stack several hundred transient decays to improve signal to noise. Stacking of several hundred transient decays requires only a few seconds, and multiple data sets can be quickly obtained.

The processing and display of TDEM data is in many respects similar to that used in other electrical and electromagnetic methods. The objective of processing TDEM data is to obtain a solution for the resistivity stratification of the subsurface that matches the observed transient.

L022S001

MODEL: 5 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)
2.81	9.3
17.77	33.1
3.01	46.1
39.42	44.8
6.76	

TIMES	DATA LATE MEASURED	CALC LATE	% ERROR
8.90E-05	7.23E+01	7.87E+01	-8.071
1.10E-04	4.75E+01	5.11E+01	-6.997
1.40E-04	3.30E+01	3.38E+01	-2.527
1.77E-04	2.39E+01	2.45E+01	-2.280
2.20E-04	1.83E+01	1.91E+01	-4.201
2.80E-04	1.49E+01	1.55E+01	-3.952
3.55E-04	1.28E+01	1.35E+01	-5.770
4.43E-04	1.13E+01	1.22E+01	-7.412
5.64E-04	1.02E+01	1.05E+01	-3.135
7.13E-04	9.22E+00	9.31E+00	-0.981
8.85E-04	8.14E+00	8.43E+00	-3.402
1.10E-03	7.39E+00	7.52E+00	-1.740
1.41E-03	6.83E+00	6.72E+00	+1.519
1.78E-03	6.36E+00	6.36E+00	+0.002
2.21E-03	6.02E+00	6.06E+00	-0.722
2.83E-03	5.82E+00	5.86E+00	-0.728
3.57E-03	5.80E+00	5.87E+00	-1.050
4.46E-03	5.74E+00	5.82E+00	-1.432
5.67E-03	5.83E+00	5.92E+00	-1.612
7.16E-03	6.01E+00	5.98E+00	+0.543
8.81E-03	5.98E+00	6.05E+00	-1.133
1.10E-02	6.26E+00	6.17E+00	+1.339

RMS ERROR: 5.7275%

Table 1. Inversion table.

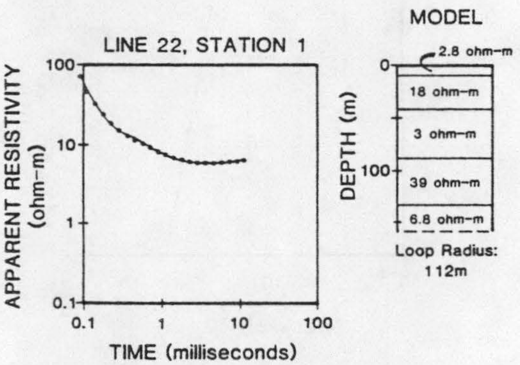


Fig. 7. Example of TDEM apparent resistivity curve and inverted geoelectric section.

The inversion of measured TDEM data into vertical resistivity stratification can be performed on a PC. An example of a data set derived for a sounding is given in Figure 7 and Table 1. In the apparent resistivity curve shown on the left (Figure 7) the measured data at each time gate is superimposed on a model curve of the geoelectric section shown on the right. This geoelectric section represents the best one-dimensional match to the experimental data. In addition to this visual display, an inversion table (Table 1) is obtained that lists (column 4) the error between measured and computed emf at each time gate, as well as an overall RMS error. The data shown on Figure 7 are typical of data quality common to TDEM soundings. Typically, 20 to 30 data points are obtained equally spaced on a logarithmic scale of time. Thus, clearly there is a major difference between TDEM soundings and profiling with the EM-31 and EM-34 (where only a few data points at different effective depths are obtained).

Question.-- If TDEM is a major improvement in electrical geophyics, why has it not been extensively used in ground water and environmental applications?

Answer.-- TDEM has been in common use in the search for base and precious metals, and for deep electrical soundings in support of hydrocarbon and geothermal exploration for about 15 years. The reason for its sparse use so far in ground water and environmental investigations was that no equipment was heretofore available for the often shallow depth (< 100 ft) requirements, common to environmental investigations.

Equipment for shallow exploration recently became available, opening a whole new range of applications for this powerful electrical measurement technique. Figure 8 shows the exploration depth range covered by various instruments.

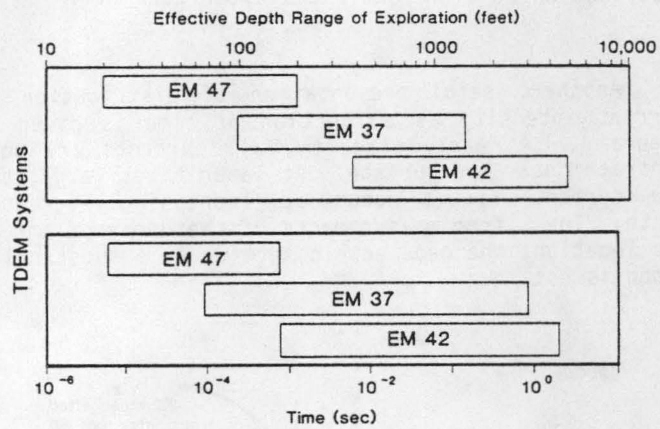


Fig. 8. Effective depth range of exploration and time range of measurement of various TDEM systems.

Question.-- What is geologic noise and why is TDEM less sensitive to such noise?

Answer.-- We define geologic noise as variation in subsurface conditions that obscures the exploration objective. Consider the schematic geologic cross section of the Floridan aquifer (Figure 9). The limestones may be overlain by overburden, likely varying laterally and vertically in soil type and thickness. At some depth in the aquifer an interface between saline and fresh water may occur, and an important exploration objective could be the mapping of this interface. Geologic noise for this objective is the change in soil type and thickness of the overburden. This noise can be very large in direct current resistivity, CSAMT and electromagnetic induction profiling.

Geologic noise is a function of the exploration objective. For example, if the objective in the setting of Figure 9 would have been the mapping of overburden thickness and type (e.g., to delineate areas of prime aquifer recharge), then what was geologic noise before becomes the exploration objective. Geologic noise is often the major cause of poor data quality in geophysical surveys for environmental and ground water applications.

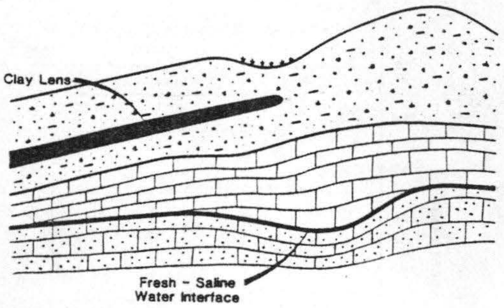


Fig. 9. Schematic geologic section of Floridan aquifer.

Question.-- How does TDEM reduce geologic noise?

Answer.-- This fact can be conceptually explained from Figure 10 where the intensity of eddy current distribution is schematically illustrated as a function of time for the FDEM and TDEM method. At early time (t_0) in TDEM all currents are concentrated near the surface, and near surface formations will largely determine the emf measured. At later time, for example, t_3, currents have largely decayed in near surface layers, and currents dominantly flow at greater depth. The emf measured at time t_3 is near transparent to near surface layers, so that their influence is greatly reduced at time t_3 and later times.

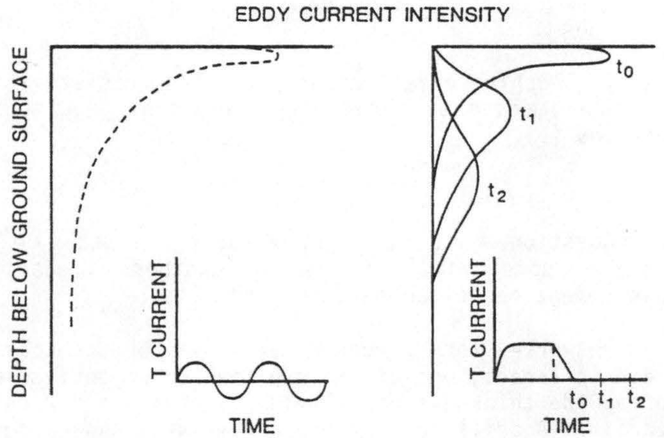


Fig. 10. Eddy current intensity in FDEM and TDEM.

In the FDEM method current intensity is always highest near the surface amplifying the influence of near surface layers.

In summary, geologic noise due to lateral and vertical resistivity variation in TDEM is reduced because:

(a) Exploration depth is mainly a function of time rather than transmitter-receiver separation. The transmitter-receiver separation need not be altered to change exploration depth as is the case in FDEM (EM-31 and EM-34), and direct current resistivity methods.

(b) Relatively small transmitter-receiver separations compared to effective exploration depth are employed.

(c) Measurements at later times are nearly transparent to near surface layers, because eddy currents at later times dominantly flow at greater depth.

Question.-- Can TDEM surveys be effective in mapping fractures and shear zones?

Answer.-- Yes, TDEM can detect contacts, fractures, and shear zones below considerable overburden thickness. The physical concepts of fracture and shear zone mapping are briefly explained.

Electrical and electromagnetic methods are often effective in mapping fractures and shear zones, because fractures and shear zones often are zones of low resistivity in more resistive host rocks. These lower resistivities are generally caused by clay gouge, higher water contents, and alteration in wall rocks. The mapping of fractures and shear zones becomes increasingly more difficult with increasing overburden thickness where outcrops are limited. It is in these situations that geophysical surveys can play an important role.

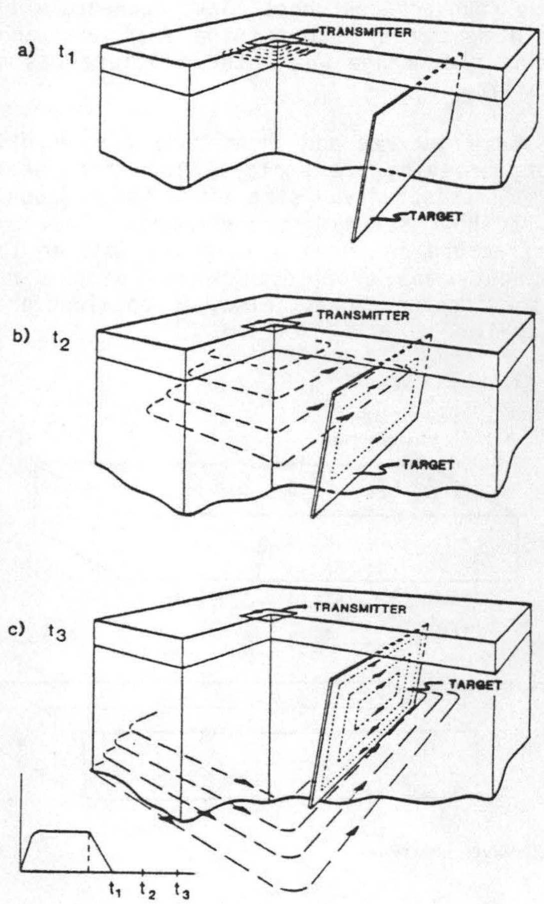


Fig. 11. Illustration of eddy current flow induced in overburden, host rock, and fracture or shear zones at different times.

Thus, in all electrical and electromagnetic methods the geoelectric section is derived by measuring resistance to current flow. We cannot selectively cause current flow in fractures and shear zones, but currents will also be induced in overburden, host rock, fractures and shear zones. The challenge is to isolate the response due to a fracture from the total response, which also contains contributions due to current flow in overburden and host rock.

TDEM is the most effective method for recognizing fractures and shear zones under overburden cover. Figure 11 conceptually explains the physical principles involved. It schematically shows a near vertical fracture zone below overburden cover, and a nearby TDEM source loop induces eddy current flow in the subsurface. At early time (t_0) eddy currents are dominantly situated in the overburden because current flow has not yet reached the fracture. Therefore, a measurement of emf at time, t_0, will not reflect the presence of a fracture zone. At later time currents are induced in the fracture, and because the fracture zone is likely less resistive than adjacent host rock, currents will be preferentially oriented in the fracture plane. In this intermediate time range the emf will contain major contributions due to currents in overburden, host rock and fractures. Currents in overburden may still dominate and fracture zones may be barely detectable. Since the fracture is less resistive than adjacent host rock, currents will decay faster in host rock than in the fracture, and there will be a time range where the fracture has maximum detectability.

To map fractures and shear zones, often different modes of surveying are employed than for determining vertical resistivity stratification (soundings). Figure 12 shows several survey modes. If the strike of the fracture is known a long transmitter loop may be laid out, and profiles are run with a receiver across the fracture zone. Also, a loop-loop array may be employed.

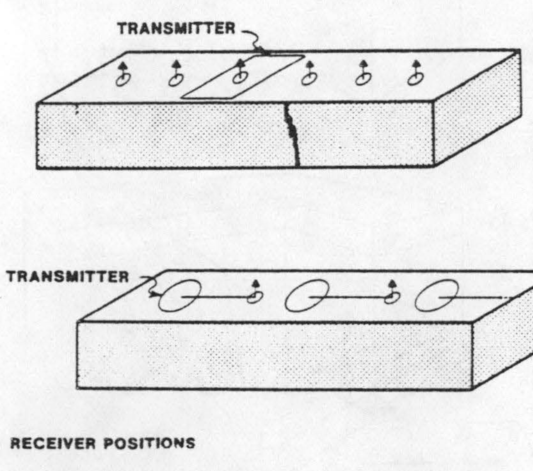


Fig. 12. Transmitter-receiver arrays useful in fracture mapping.

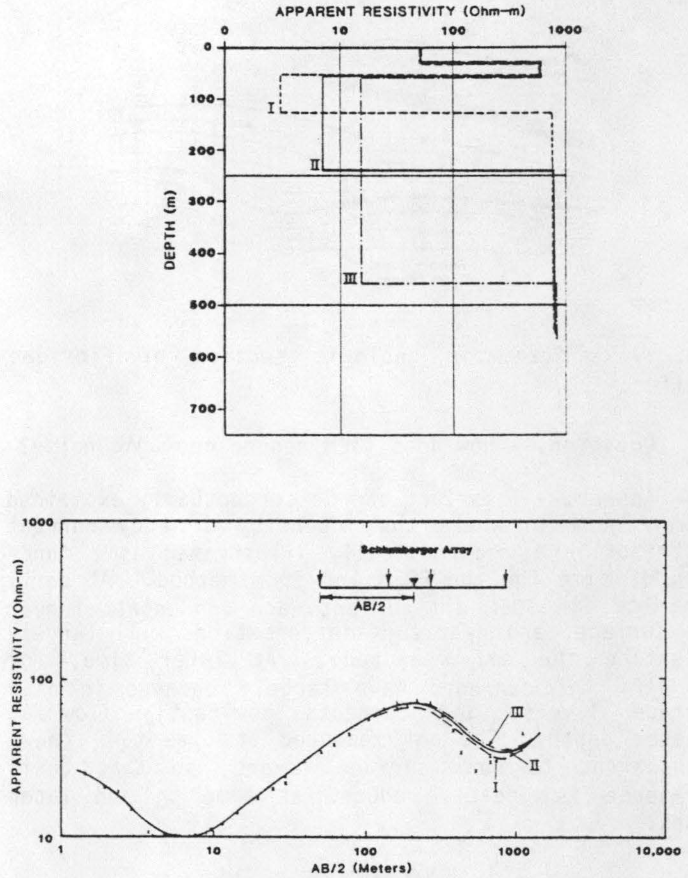


Fig. 13. Schlumberger measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections (b).

Question.-- I am from Missouri. Show me an example comparing TDEM with another electrical measurement technique next to a drill hole.

Answer.-- In a ground water survey on the coastal plain in Israel, one of the exploration objectives was to map the thickness of alluvium overlying a carbonate bedrock. A drill hole at the survey site showed depth to bedrock at about 168 m (550 ft).

The Institute of Petroleum Research and Geophysics, prior to the arrival of our TDEM crew, conducted a Schlumberger resistivity sounding near the drill hole. The results are given in Figure 13. Measurements were made to AL/2-spacing of 2,000 m (an array length of 4,000 m). The measured apparent resistivity data are superimposed on the forward models of three geoelectric sections. The three geoelectric sections are shown on the right. Clearly, the data can be fitted to any of the three models. Yet, depth to bedrock between the three sections was varied by more than 300 m. The Institute, therefore, quickly decided that Schlumberger resistivity soundings were not a viable method, because not only was a large effort required to explore to a depth of 168 m (4,000 m of line length), but its vertical resolution was meaningless.

Measurements at the same location were made with TDEM in 200 m by 200 m transmitter loops, and the results of central-loop TDEM soundings are shown in Figure 14. Again, the measured apparent resistivity curves are superimposed on three forward model curves, and the geoelectric sections of the three model curves are shown on the right. Depth to bedrock in the models is varied by 20 m. It is evident that vertical resolution of determining depth to bedrock is now $\pm$ 10 m.

Thus, not only was the physical effort required to sound to a depth of 168 m greatly reduced - only 800 m (4 x 200 m) of wire needed to be laid out, - but the vertical resolution was greatly improved.

Question.-- Summarize for me the potential of TDEM in environmental and ground water geophysics.

Answer.--Electrical surface geophysical methods are an important tool because (1) electrical resistivity is the only readily measureable physical property highly dependent of concentration of dissolved solids (water quality), and (2) electrical resistivity often closely relates to clay content and hydraulic permeability. In the past the vertical and lateral resolution of electrical methods was poor. TDEM techniques are changing that reputation.

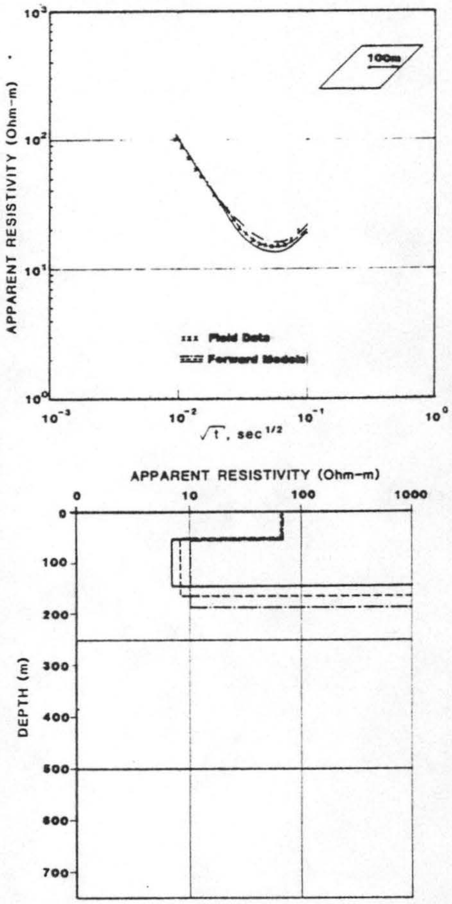
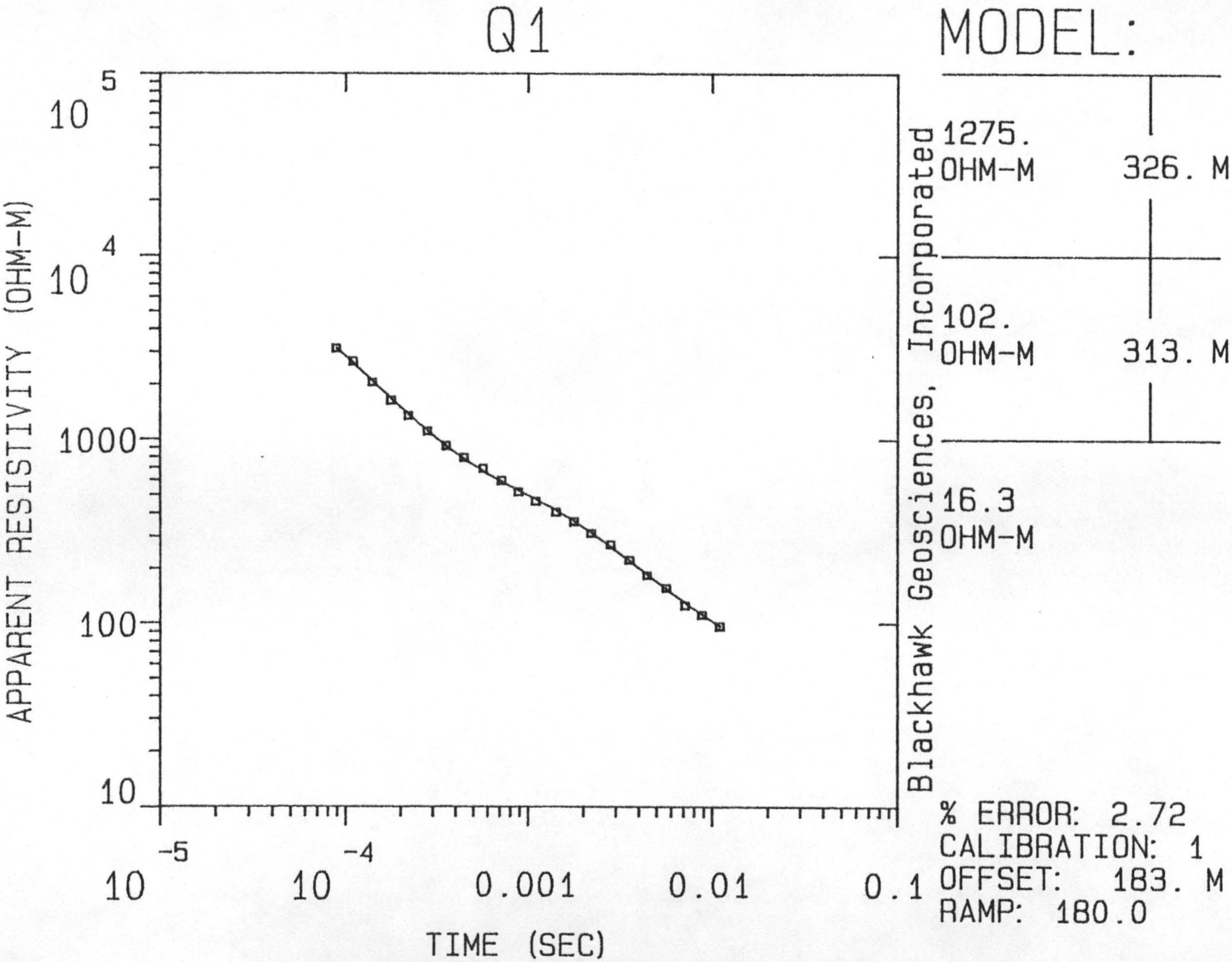


Fig. 14. TDEM measured apparent resistivities (a) superimposed on three one-dimensional geoelectric sections.


Q1
MODEL:
10^5
10^4
1000
100
10
APPARENT RESISTIVITY (OHM-M)
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
1275.
OHM-M
326. M
102.
OHM-M
313. M
16.3
OHM-M
% ERROR: 2.72
CALIBRATION: 1
OFFSET: 183. M
RAMP: 180.0

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		475.5	1560.0		
1274.99	325.8	149.7	491.3	0.3	0.3
102.11	313.0	-163.3	-535.7	3.1	3.3
16.33					

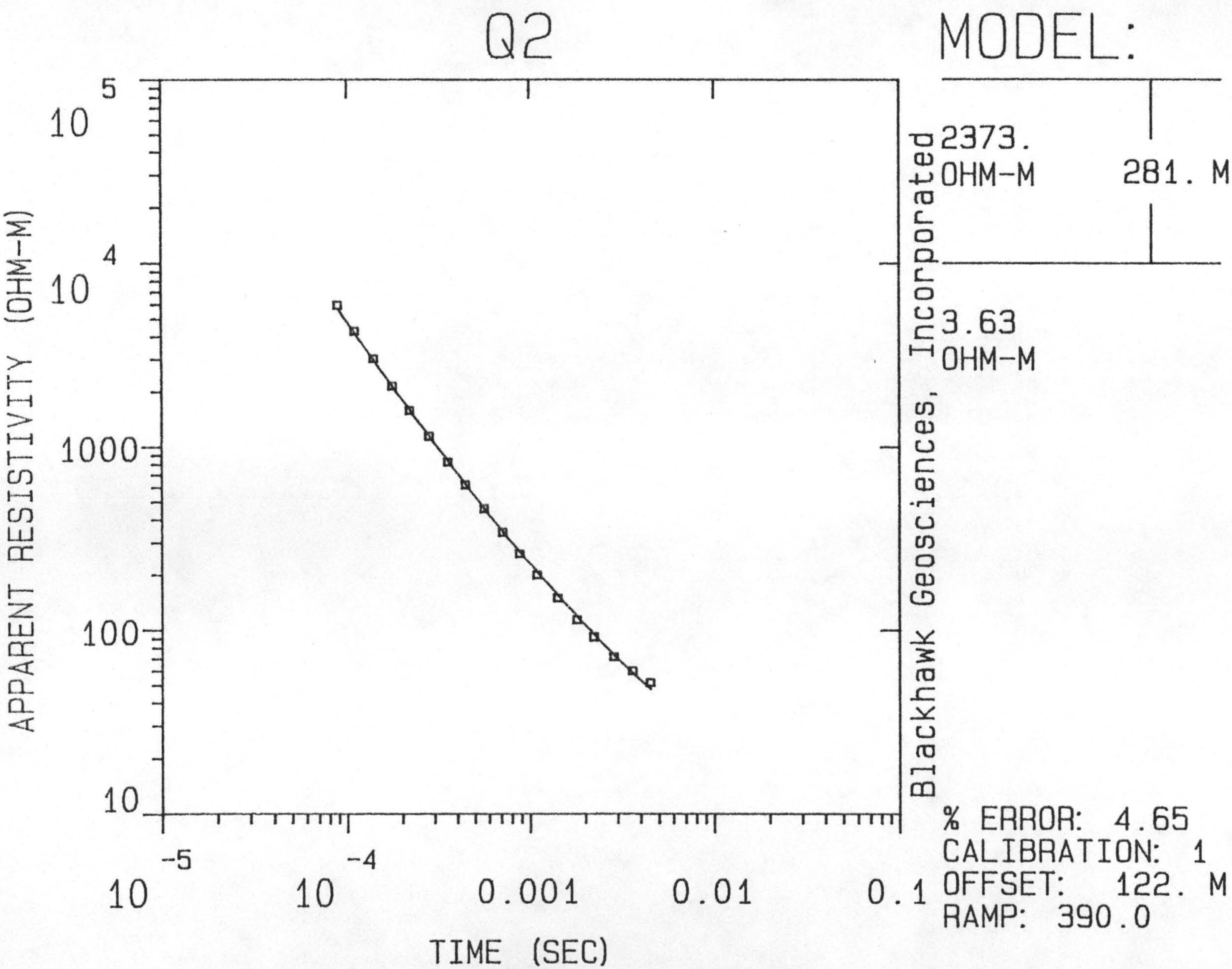
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	3.13E+03	3.14E+03	-0.554	
2	1.10E-04	2.66E+03	2.60E+03	2.499	
3	1.40E-04	2.05E+03	2.07E+03	-1.103	
4	1.77E-04	1.63E+03	1.66E+03	-2.067	
5	2.20E-04	1.34E+03	1.36E+03	-1.703	
6	2.80E-04	1.10E+03	1.10E+03	-0.110	
7	3.55E-04	9.21E+02	9.12E+02	0.937	
8	4.43E-04	7.93E+02	7.77E+02	1.955	
9	5.64E-04	6.91E+02	6.67E+02	3.520	
10	7.13E-04	5.94E+02	5.86E+02	1.495	
11	8.81E-04	5.18E+02	5.26E+02	-1.569	
12	1.10E-03	4.61E+02	4.72E+02	-2.369	
13	1.41E-03	4.04E+02	4.13E+02	-2.180	
14	1.77E-03	3.60E+02	3.61E+02	-0.294	
15	2.20E-03	3.11E+02	3.13E+02	-0.431	
16	2.80E-03	2.70E+02	2.63E+02	2.876	
17	3.55E-03	2.23E+02	2.19E+02	1.477	
18	4.43E-03	1.83E+02	1.85E+02	-0.788	
19	5.64E-03	1.56E+02	1.54E+02	1.387	
20	7.13E-03	1.25E+02	1.29E+02	-3.159	
21	8.81E-03	1.11E+02	1.11E+02	-0.046	
22	1.10E-02	9.62E+01	9.58E+01	0.394	

R: 183. X: 0. Y: 183. DL: 366. REQ: 203. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 180.0 MICROSEC, DATA: Q1
2614 002N 001E Z OPR XTL H 6 8+100
Ch.21 = 0.18 Ch.22 = 0.089 Ch.23 = 14.5 Ch.24 =
RMS LOG ERROR: 1.16E-02, ANTILOG YIELDS 2.7175 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.32				
P 2	-0.17	0.51			
P 3	0.00	-0.11	0.13		
T 1	0.15	0.15	0.00	0.91	
T 2	-0.11	-0.07	0.08	0.05	0.77
	P 1	P 2	P 3	T 1	T 2



Q2
10^5
10^4
1000
100
10
APPARENT RESISTIVITY (OHM-M)
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
MODEL:
2373.
OHM-M
281. M
3.63
OHM-M
% ERROR: 4.65
CALIBRATION: 1
OFFSET: 122. M
RAMP: 390.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		268.2	880.0		
2373.38	281.0	-12.7	-41.8	0.1	0.1
3.63					

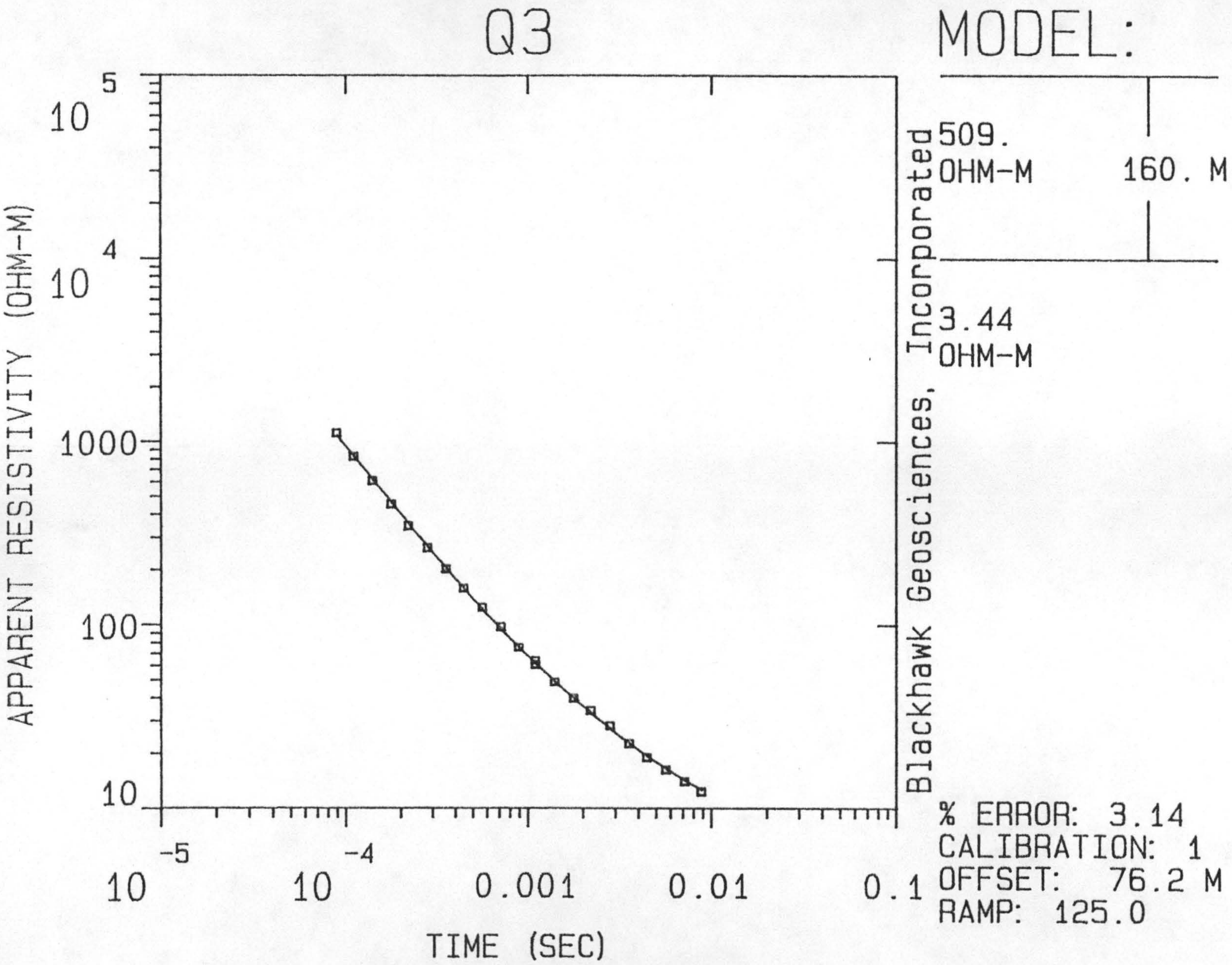
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	5.93E+03	5.66E+03	4.608	
2	1.10E-04	4.28E+03	4.18E+03	2.502	
3	1.40E-04	3.02E+03	2.96E+03	1.999	
4	1.77E-04	2.15E+03	2.13E+03	0.757	
5	2.20E-04	1.58E+03	1.58E+03	-0.027	
6	2.80E-04	1.14E+03	1.14E+03	-0.101	
7	3.55E-04	8.25E+02	8.33E+02	-0.944	
8	4.43E-04	6.20E+02	6.24E+02	-0.718	
9	5.64E-04	4.60E+02	4.60E+02	0.023	
10	7.13E-04	3.42E+02	3.44E+02	-0.458	
11	8.81E-04	2.61E+02	2.66E+02	-2.157	
12	1.10E-03	2.00E+02	2.06E+02	-3.252	
13	1.41E-03	1.50E+02	1.55E+02	-3.185	
14	1.80E-03	1.14E+02	1.19E+02	-3.975	
15	2.22E-03	9.19E+01	9.47E+01	-2.884	
16	2.85E-03	7.18E+01	7.33E+01	-2.129	
17	3.60E-03	6.00E+01	5.85E+01	2.624	
18	4.49E-03	5.17E+01	4.76E+01	8.719	

R: 122. X: 0. Y: 122. DL: 244. REQ: 136. CF: 1.0000
CLHZ ARRAY, 18 DATA POINTS, RAMP: 390.0 MICROSEC, DATA: Q2
2704 002E 002E Z OPR XTL H 5 8+100
Ch.21 = 0.39 Ch.22 = 0.089 Ch.23 = 20 Ch.24 = 5
RMS LOG ERROR: 1.97E-02, ANTILOG YIELDS 4.6450 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.06		
P 2	-0.09	0.83	
T 1	0.00	-0.01	1.00
	P 1	P 2	T 1


Q3
MODEL:
5
10
4
10
1000
100
10
APPARENT RESISTIVITY (OHM-M)
Blackhawk Geosciences, Incorporated
509.
OHM-M
160. M
3.44
OHM-M
-5
10
-4
10
0.001
0.01
0.1
TIME (SEC)
% ERROR: 3.14
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 125.0

Q3

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		155.4	510.0		
509.22	159.7	-4.2	-13.9	0.3	0.3
3.44					

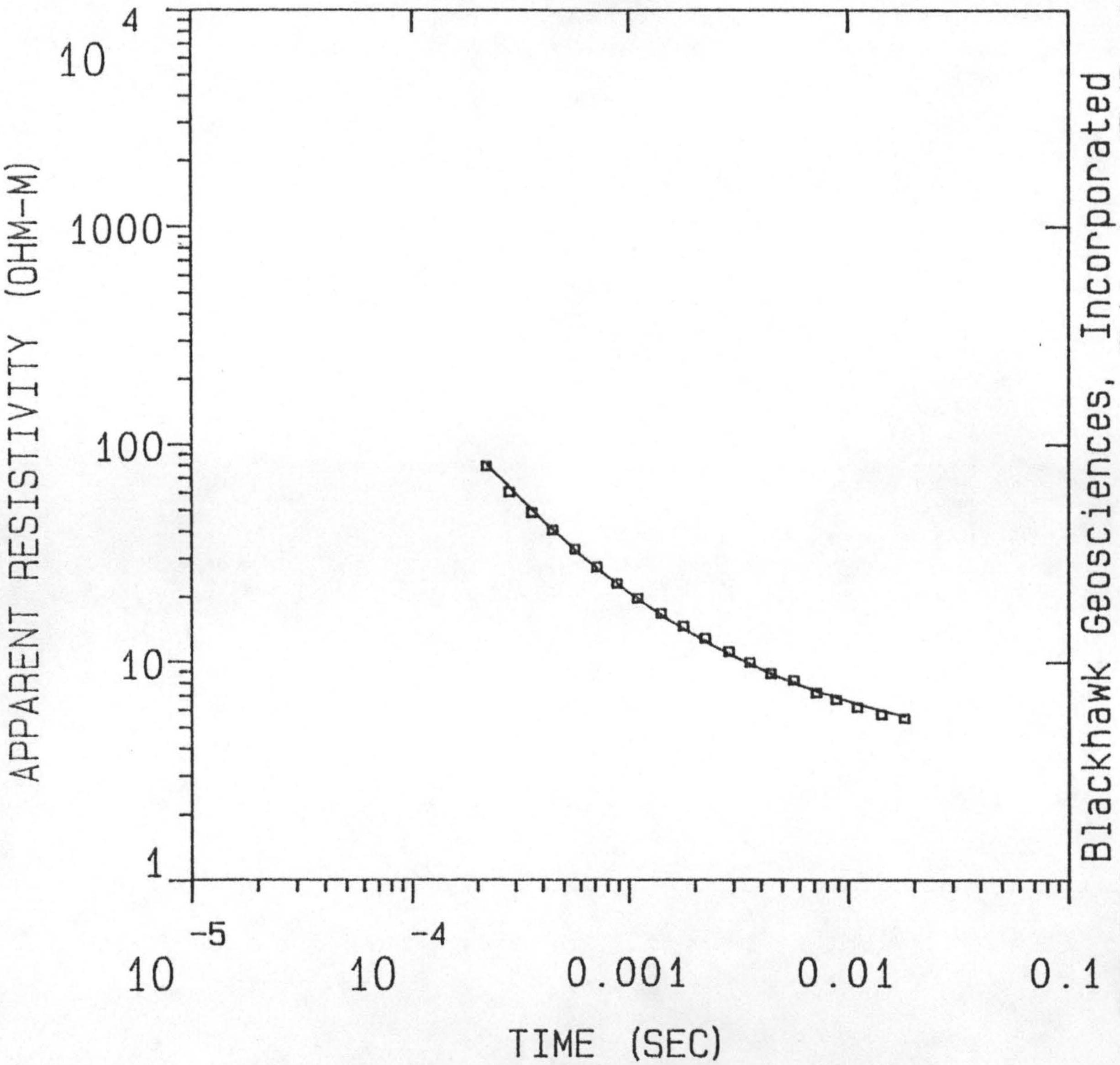
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	1.11E+03	1.08E+03	2.955	
2	1.10E-04	8.25E+02	8.33E+02	-0.932	
3	1.40E-04	6.06E+02	6.19E+02	-1.987	
4	1.77E-04	4.54E+02	4.64E+02	-2.127	
5	2.20E-04	3.47E+02	3.57E+02	-2.739	
6	2.80E-04	2.63E+02	2.68E+02	-1.942	
7	3.55E-04	2.02E+02	2.04E+02	-0.810	
8	4.43E-04	1.59E+02	1.59E+02	-0.036	
9	5.64E-04	1.25E+02	1.22E+02	2.534	
10	7.13E-04	9.80E+01	9.52E+01	2.924	
11	8.90E-04	7.58E+01	7.59E+01	-0.170	
12	1.10E-03	6.42E+01	6.19E+01	3.724	
13	1.10E-03	6.08E+01	6.17E+01	-1.402	
14	1.40E-03	4.89E+01	4.91E+01	-0.382	
15	1.77E-03	3.99E+01	3.98E+01	0.274	
16	2.20E-03	3.41E+01	3.30E+01	3.128	
17	2.80E-03	2.82E+01	2.72E+01	3.760	
18	3.55E-03	2.27E+01	2.27E+01	-0.199	
19	4.43E-03	1.90E+01	1.94E+01	-1.849	
20	5.64E-03	1.63E+01	1.65E+01	-1.202	
21	7.13E-03	1.41E+01	1.43E+01	-1.114	
22	8.81E-03	1.24E+01	1.27E+01	-1.977	

R: 76. X: 0. Y: 76. DL: 152. REQ: 84. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 125.0 MICROSEC, DATA: Q3
2804 002N 003E Z OPR XTL H 5 8+100
Ch.21 = 0.125 Ch.22 = 0.089 Ch.23 = 21 Ch.24 =
RMS LOG ERROR: 1.34E-02, ANTILOG YIELDS 3.1450 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.02		
P 2	-0.05	0.41	
T 1	0.03	0.01	0.98
	P 1	P 2	T 1



MODEL:

537.
OHM-M

76.1 M

3.25
OHM-M

% ERROR: 3.90
CALIBRATION: 1
OFFSET: 30.5 M
RAMP: 125.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		73.2	240.0		
536.99	76.1	-2.9	-9.6	0.1	0.1
3.25					

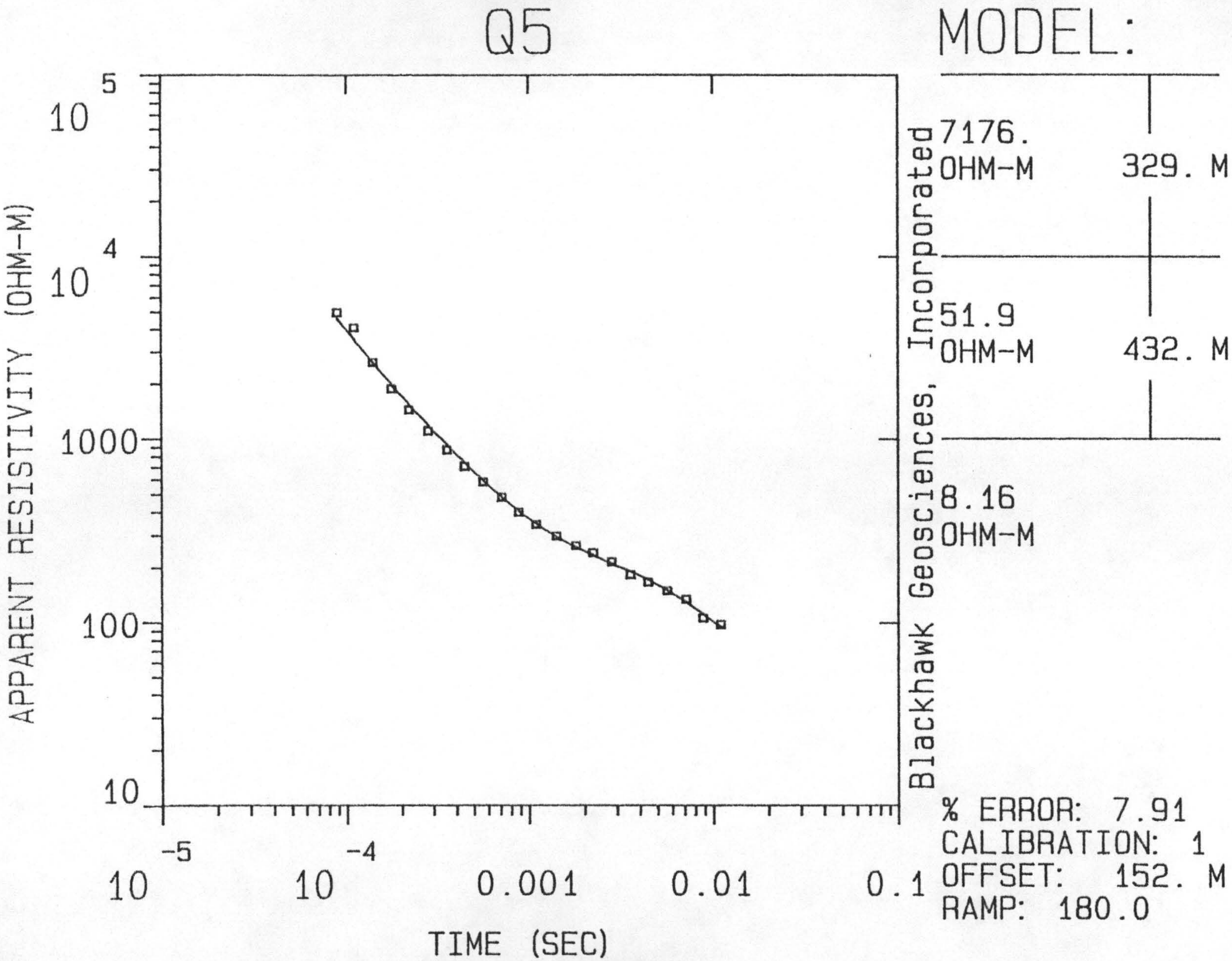
	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.20E-04	7.92E+01	8.13E+01	-2.542	
2	2.80E-04	6.03E+01	6.32E+01	-4.553	
3	3.55E-04	4.87E+01	4.99E+01	-2.489	
4	4.43E-04	4.04E+01	4.05E+01	-0.274	
5	5.64E-04	3.31E+01	3.27E+01	1.174	
6	7.13E-04	2.74E+01	2.69E+01	1.823	
7	8.81E-04	2.30E+01	2.28E+01	0.712	
8	1.10E-03	1.97E+01	1.94E+01	1.374	
9	1.40E-03	1.68E+01	1.64E+01	2.078	
10	1.77E-03	1.46E+01	1.42E+01	3.220	
11	2.22E-03	1.29E+01	1.24E+01	3.804	
12	2.85E-03	1.12E+01	1.09E+01	2.880	
13	3.55E-03	9.95E+00	9.77E+00	1.882	
14	4.43E-03	8.87E+00	8.85E+00	0.280	
15	5.64E-03	8.30E+00	8.02E+00	3.451	
16	7.13E-03	7.25E+00	7.35E+00	-1.434	
17	8.81E-03	6.73E+00	6.85E+00	-1.625	
18	1.10E-02	6.20E+00	6.40E+00	-3.219	
19	1.41E-02	5.73E+00	5.97E+00	-4.043	
20	1.80E-02	5.51E+00	5.62E+00	-2.040	

R: 30. X: 0. Y: 30. DL: 61. REQ: 33. CF: 1.0000
CLHZ ARRAY, 20 DATA POINTS, RAMP: 125.0 MICROSEC, DATA: Q4
2804 002N 004E Z OPR XTL H 3 8+100
Ch.21 = 0.125 Ch.22 = 0.089 Ch.23 = 25.5 Ch.24
RMS LOG ERROR: 1.66E-02, ANTILOG YIELDS 3.8961 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.00		
P 2	0.00	0.99	
T 1	0.01	0.00	1.00
	P 1	P 2	T 1



Q5
MODEL:
APPARENT RESISTIVITY (OHM-M)
TIME (SEC)
Blackhawk Geosciences, Incorporated
7176.
OHM-M
329. M
51.9
OHM-M
432. M
8.16
OHM-M
% ERROR: 7.91
CALIBRATION: 1
OFFSET: 152. M
RAMP: 180.0

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		371.9	1220.0		
7176.12	328.5	43.3	142.1	0.0	0.0
51.92	431.7	-388.3	-1274.1	8.3	8.4
8.16					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	4.94E+03	4.58E+03	7.840	
2	1.10E-04	4.08E+03	3.50E+03	16.535	
3	1.40E-04	2.62E+03	2.60E+03	0.723	
4	1.77E-04	1.88E+03	1.97E+03	-4.768	
5	2.20E-04	1.44E+03	1.54E+03	-6.389	
6	2.80E-04	1.10E+03	1.18E+03	-6.563	
7	3.55E-04	8.68E+02	9.21E+02	-5.742	
8	4.43E-04	7.08E+02	7.39E+02	-4.184	
9	5.64E-04	5.82E+02	5.90E+02	-1.392	
10	7.13E-04	4.82E+02	4.80E+02	0.425	
11	8.81E-04	4.00E+02	4.04E+02	-0.957	
12	1.10E-03	3.44E+02	3.45E+02	-0.122	
13	1.41E-03	2.97E+02	2.92E+02	1.733	
14	1.80E-03	2.64E+02	2.57E+02	2.647	
15	2.22E-03	2.40E+02	2.33E+02	3.326	
16	2.80E-03	2.15E+02	2.09E+02	2.852	
17	3.55E-03	1.84E+02	1.91E+02	-3.697	
18	4.43E-03	1.67E+02	1.72E+02	-2.973	
19	5.64E-03	1.50E+02	1.50E+02	0.162	
20	7.13E-03	1.35E+02	1.29E+02	3.947	
21	8.81E-03	1.06E+02	1.11E+02	-4.418	
22	1.10E-02	9.80E+01	9.39E+01	4.315	

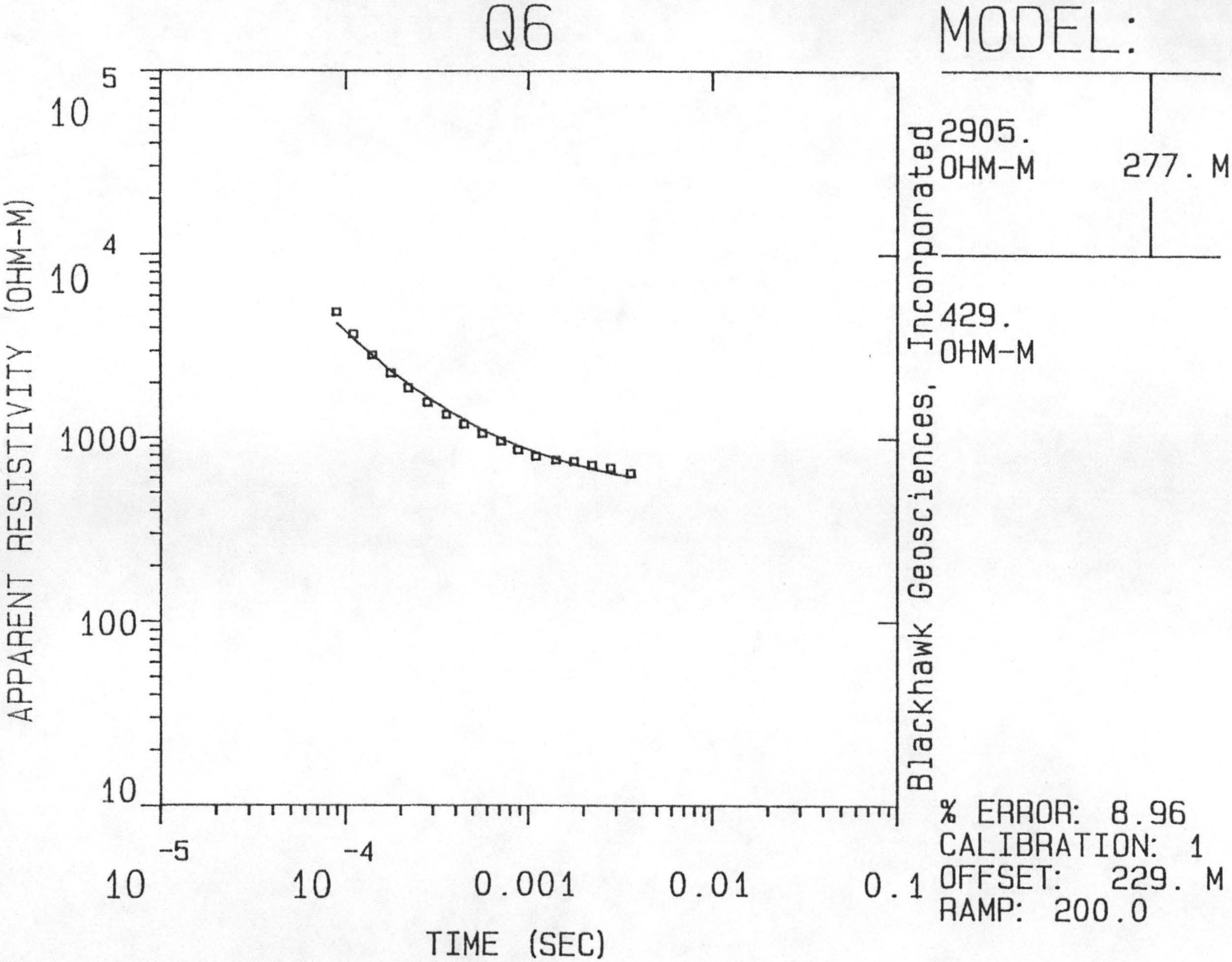
R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 180.0 MICROSEC, DATA: Q5
2904 002N 005E Z OPR XTL H 6 8+100
Ch.21 = 0.18 Ch.22 = 0.089 Ch.23 = 17 Ch.24 = 9
RMS LOG ERROR: 3.31E-02, ANTILOG YIELDS 7.9087 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.92				
P 2	-0.01	1.00			
P 3	-0.01	-0.01	0.96		
T 1	0.00	0.00	0.00	1.00	
T 2	-0.01	0.00	0.00	0.00	1.00
	P 1	P 2	P 3	T 1	T 2

Q6



MODEL:
2905.
OHM-M
277. M
429.
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 8.96
CALIBRATION: 1
OFFSET: 229. M
RAMP: 200.0

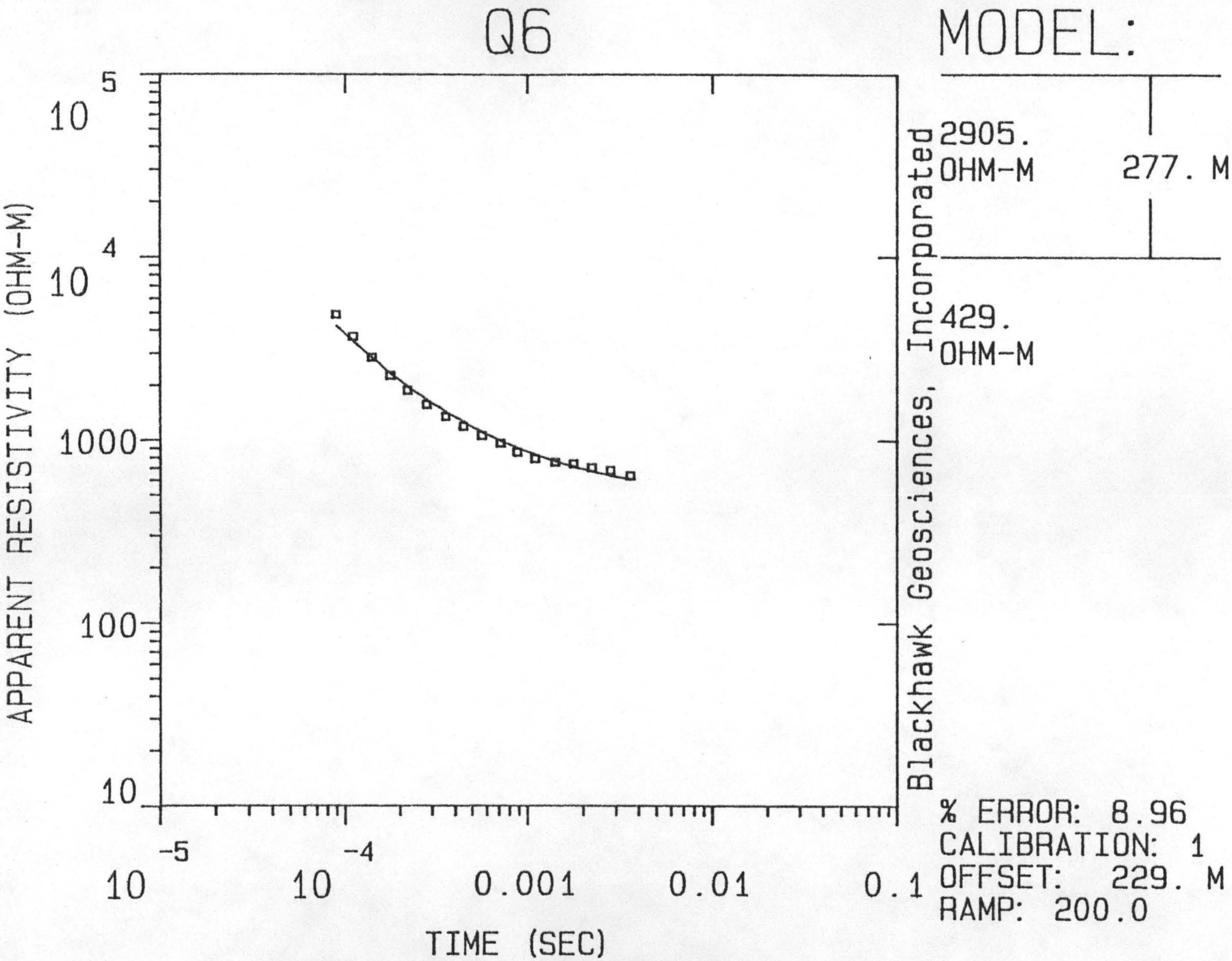
MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		585.2	1920.0		
2904.58	276.6	308.6	1012.5	0.1	0.1
428.54					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	4.87E+03	4.23E+03	15.127	
2	1.10E-04	3.70E+03	3.47E+03	6.374	
3	1.40E-04	2.84E+03	2.81E+03	0.999	
4	1.77E-04	2.26E+03	2.32E+03	-2.401	
5	2.20E-04	1.88E+03	1.96E+03	-4.468	
6	2.80E-04	1.57E+03	1.66E+03	-5.467	
7	3.55E-04	1.34E+03	1.42E+03	-5.757	
8	4.43E-04	1.18E+03	1.25E+03	-5.256	
9	5.64E-04	1.05E+03	1.10E+03	-4.194	
10	7.13E-04	9.57E+02	9.85E+02	-2.760	
11	8.81E-04	8.56E+02	9.00E+02	-4.928	
12	1.10E-03	7.89E+02	8.28E+02	-4.642	
13	1.41E-03	7.55E+02	7.61E+02	-0.741	
14	1.77E-03	7.41E+02	7.12E+02	4.112	
15	2.22E-03	7.06E+02	6.70E+02	5.350	
16	2.80E-03	6.83E+02	6.36E+02	7.400	
17	3.60E-03	6.37E+02	6.05E+02	5.296	

R: 229. X: 0. Y: 229. DL: 457. REQ: 254. CF: 1.0000
CLHZ ARRAY, 17 DATA POINTS, RAMP: 200.0 MICROSEC, DATA: Q6
3004 002N 006E Z OPR XTL L 6 10+100
Ch.21 = 0.2 Ch.22 = 0.89 Ch.23 = 13.5 Ch.24 = 2
RMS LOG ERROR: 3.73E-02, ANTILOG YIELDS 8.9587 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *
CURRENT RESOLUTION MATRICES NOT AVAILABLE



Q6
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-5}
10^{-4}
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
2905.
OHM-M
277. M
429.
OHM-M
% ERROR: 8.96
CALIBRATION: 1
OFFSET: 229. M
RAMP: 200.0

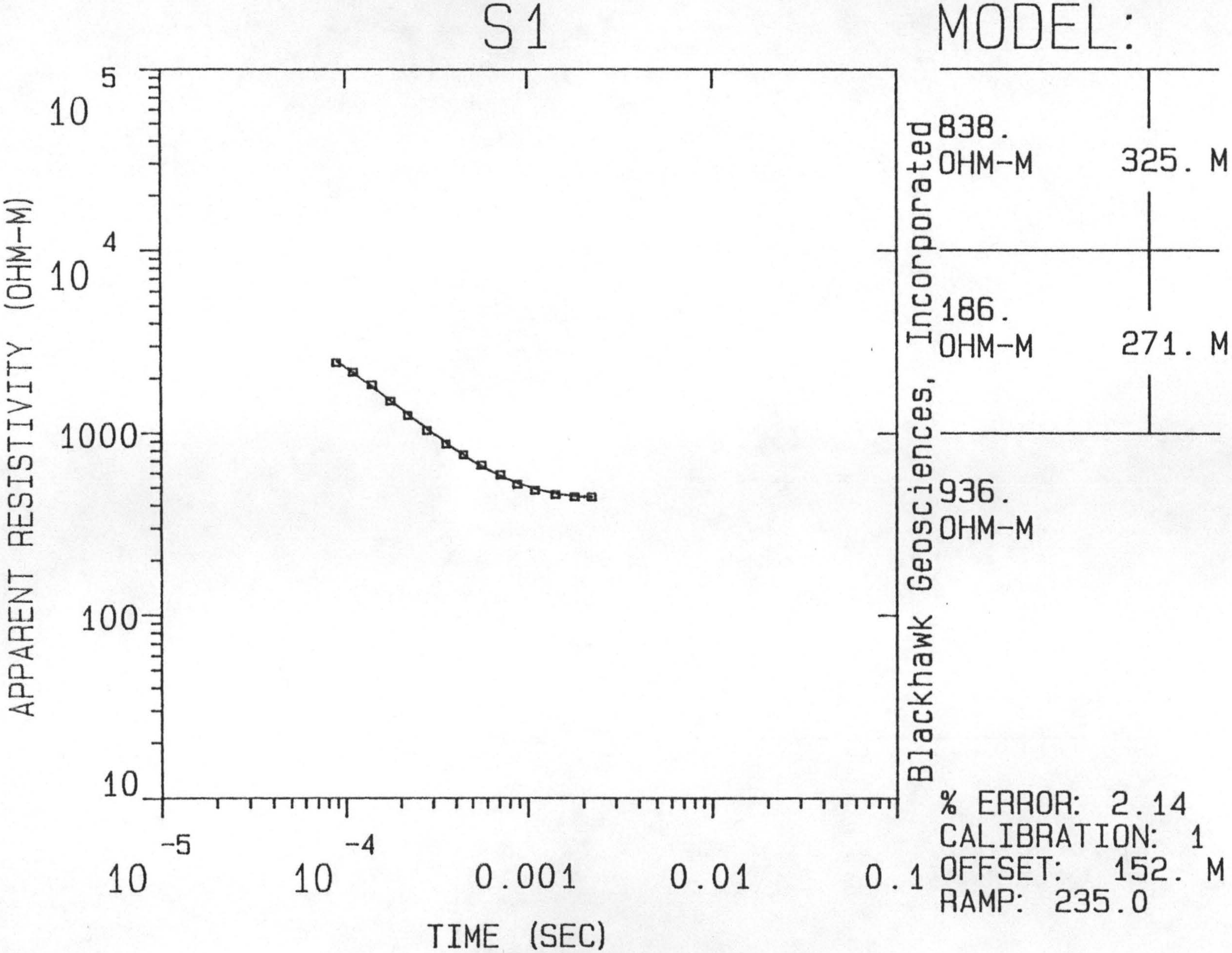
MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		585.2	1920.0		
2904.58	276.6	308.6	1012.5	0.1	0.1
428.54					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	4.87E+03	4.23E+03	15.127	
2	1.10E-04	3.70E+03	3.47E+03	6.374	
3	1.40E-04	2.84E+03	2.81E+03	0.999	
4	1.77E-04	2.26E+03	2.32E+03	-2.401	
5	2.20E-04	1.88E+03	1.96E+03	-4.468	
6	2.80E-04	1.57E+03	1.66E+03	-5.467	
7	3.55E-04	1.34E+03	1.42E+03	-5.757	
8	4.43E-04	1.18E+03	1.25E+03	-5.256	
9	5.64E-04	1.05E+03	1.10E+03	-4.194	
10	7.13E-04	9.57E+02	9.85E+02	-2.760	
11	8.81E-04	8.56E+02	9.00E+02	-4.928	
12	1.10E-03	7.89E+02	8.28E+02	-4.642	
13	1.41E-03	7.55E+02	7.61E+02	-0.741	
14	1.77E-03	7.41E+02	7.12E+02	4.112	
15	2.22E-03	7.06E+02	6.70E+02	5.350	
16	2.80E-03	6.83E+02	6.36E+02	7.400	
17	3.60E-03	6.37E+02	6.05E+02	5.296	

R: 229. X: 0. Y: 229. DL: 457. REQ: 254. CF: 1.0000
CLHZ ARRAY, 17 DATA POINTS, RAMP: 200.0 MICROSEC, DATA: Q6
3004 002N 006E Z OPR XTL L 6 10+100
Ch.21 = 0.2 Ch.22 = 0.89 Ch.23 = 13.5 Ch.24 = 2
RMS LOG ERROR: 3.73E-02, ANTILOG YIELDS 8.9587 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *
CURRENT RESOLUTION MATRICES NOT AVAILABLE


S1
MODEL:
10^5
10^4
1000
100
10
APPARENT RESISTIVITY (OHM-M)
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
838.
OHM-M
325. M
186.
OHM-M
271. M
936.
OHM-M
Blackhawk Geosciences, Incorporated
% ERROR: 2.14
CALIBRATION: 1
OFFSET: 152. M
RAMP: 235.0

MODEL: 3 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		560.8	1840.0		
837.85	325.1	235.7	773.4	0.4	0.4
185.82	270.9	-35.2	-115.4	1.5	1.8
935.78					

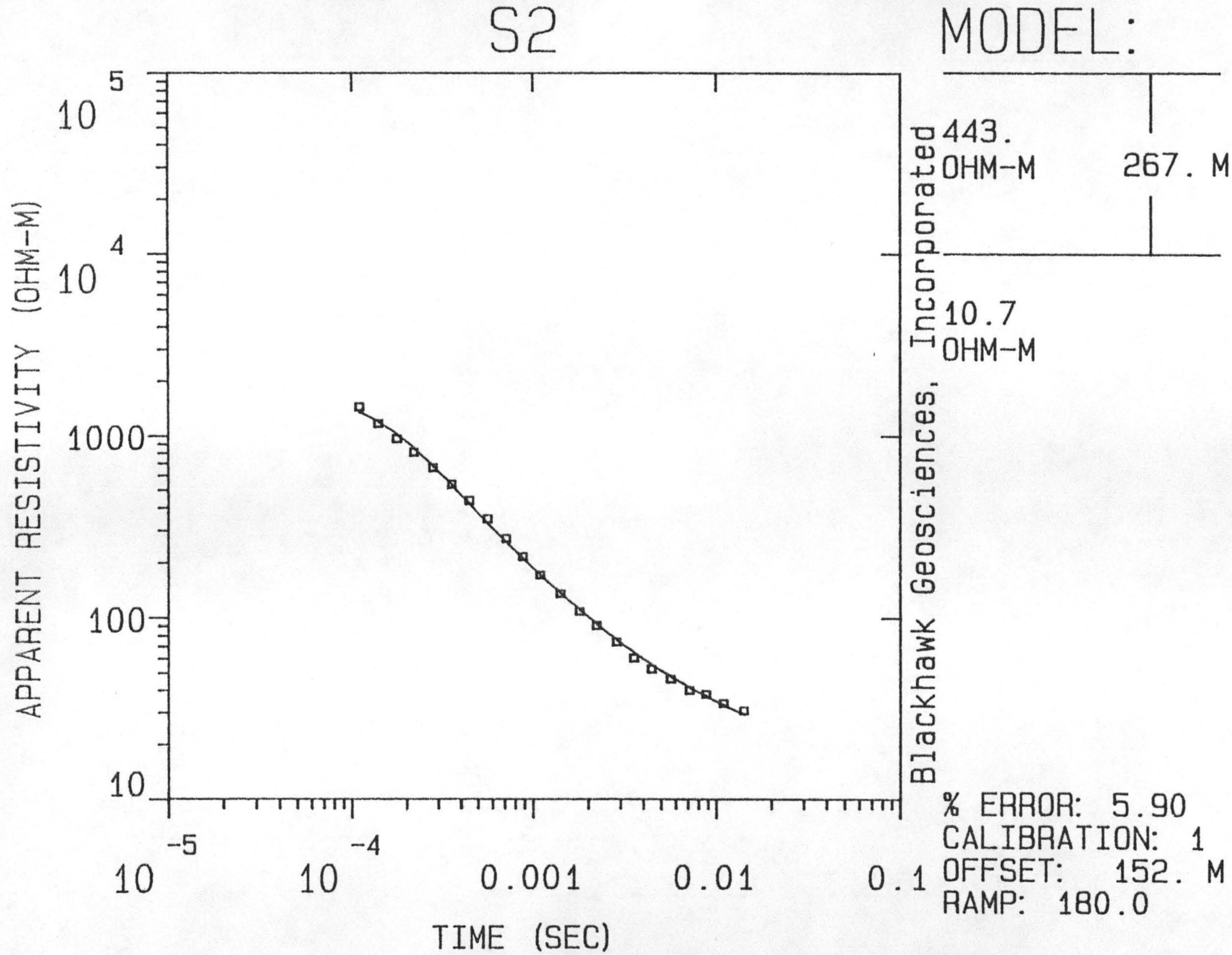
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	2.43E+03	2.48E+03	-1.891	
2	1.10E-04	2.16E+03	2.13E+03	1.033	
3	1.40E-04	1.84E+03	1.79E+03	2.908	
4	1.77E-04	1.50E+03	1.50E+03	0.004	
5	2.20E-04	1.25E+03	1.26E+03	-1.259	
6	2.80E-04	1.03E+03	1.05E+03	-1.807	
7	3.55E-04	8.70E+02	8.78E+02	-0.983	
8	4.43E-04	7.57E+02	7.54E+02	0.417	
9	5.64E-04	6.63E+02	6.51E+02	1.924	
10	7.13E-04	5.87E+02	5.76E+02	1.891	
11	8.81E-04	5.23E+02	5.27E+02	-0.732	
12	1.10E-03	4.84E+02	4.90E+02	-1.225	
13	1.41E-03	4.57E+02	4.61E+02	-0.850	
14	1.80E-03	4.45E+02	4.46E+02	-0.273	
15	2.22E-03	4.44E+02	4.40E+02	0.918	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
CLHZ ARRAY, 15 DATA POINTS, RAMP: 235.0 MICROSEC, DATA: S1
0205 003N 001E Z OPR XTL H 6 8+100
Ch.21 = 0.235 Ch.22 = 0.089 Ch.23 = 15 Ch.24 =
RMS LOG ERROR: 9.19E-03, ANTILOG YIELDS 2.1381 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

	P 1	P 2	P 3	T 1	T 2
P 1	1.00				
P 2	0.00	0.99			
P 3	0.00	-0.03	0.80		
T 1	0.00	0.00	0.01	1.00	
T 2	0.00	-0.02	-0.07	0.01	0.97



S2
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
443.
OHM-M
267. M
10.7
OHM-M
% ERROR: 5.90
CALIBRATION: 1
OFFSET: 152. M
RAMP: 180.0

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		396.2	1300.0		
442.60	266.7	129.5	424.9	0.6	0.6
10.71					

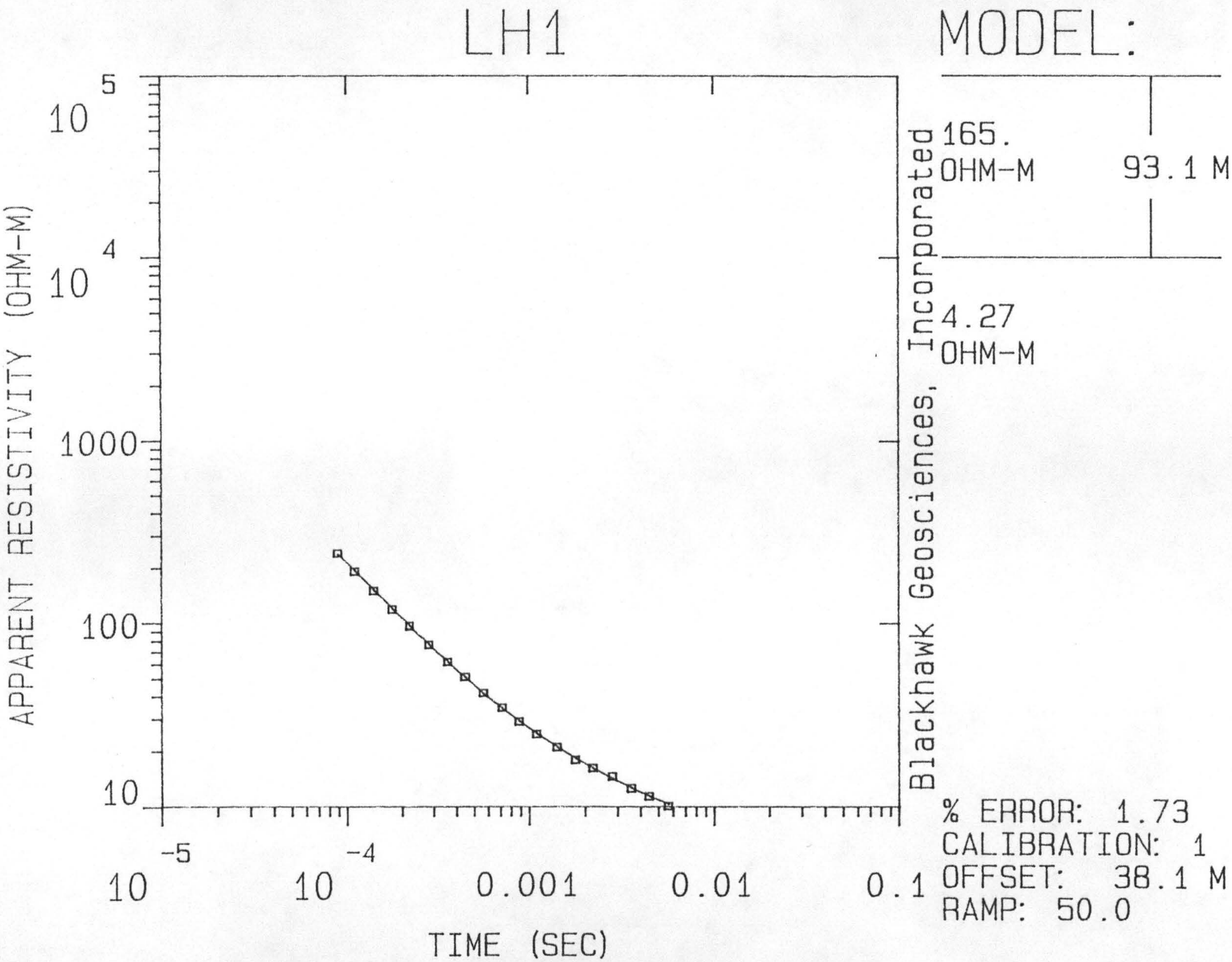
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	1.44E+03	1.35E+03	6.328	
2	1.40E-04	1.16E+03	1.19E+03	-2.270	
3	1.77E-04	9.61E+02	1.02E+03	-5.361	
4	2.20E-04	8.07E+02	8.48E+02	-4.833	
5	2.80E-04	6.62E+02	6.75E+02	-1.938	
6	3.55E-04	5.36E+02	5.30E+02	1.001	
7	4.43E-04	4.38E+02	4.21E+02	3.873	
8	5.64E-04	3.48E+02	3.28E+02	5.875	
9	7.13E-04	2.71E+02	2.59E+02	4.699	
10	8.81E-04	2.16E+02	2.10E+02	2.467	
11	1.10E-03	1.72E+02	1.71E+02	0.572	
12	1.41E-03	1.36E+02	1.36E+02	-0.114	
13	1.80E-03	1.08E+02	1.10E+02	-1.606	
14	2.22E-03	9.11E+01	9.23E+01	-1.244	
15	2.85E-03	7.43E+01	7.61E+01	-2.301	
16	3.55E-03	6.06E+01	6.47E+01	-6.347	
17	4.43E-03	5.27E+01	5.56E+01	-5.211	
18	5.64E-03	4.64E+01	4.76E+01	-2.633	
19	7.13E-03	4.03E+01	4.14E+01	-2.763	
20	8.81E-03	3.82E+01	3.69E+01	3.566	
21	1.10E-02	3.39E+01	3.30E+01	2.935	
22	1.41E-02	3.09E+01	2.93E+01	5.393	

R: 152. X: 0. Y: 152. DL: 305. REQ: 169. CF: 1.0000
CLHZ ARRAY, 22 DATA POINTS, RAMP: 180.0 MICROSEC, DATA: S2
0305 003N 002E Z OPR XTL H 6 8+100
Ch.21 = 0.18 Ch.22 = 0.089 Ch.23 = 17 Ch.24 = 9
RMS LOG ERROR: 2.49E-02, ANTILOG YIELDS 5.9015 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1



LH1
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
165.
OHM-M
93.1 M
4.27
OHM-M
% ERROR: 1.73
CALIBRATION: 1
OFFSET: 38.1 M
RAMP: 50.0

LH1

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		76.2	250.0		
164.91	93.1	-16.9	-55.5	0.6	0.6
4.27					

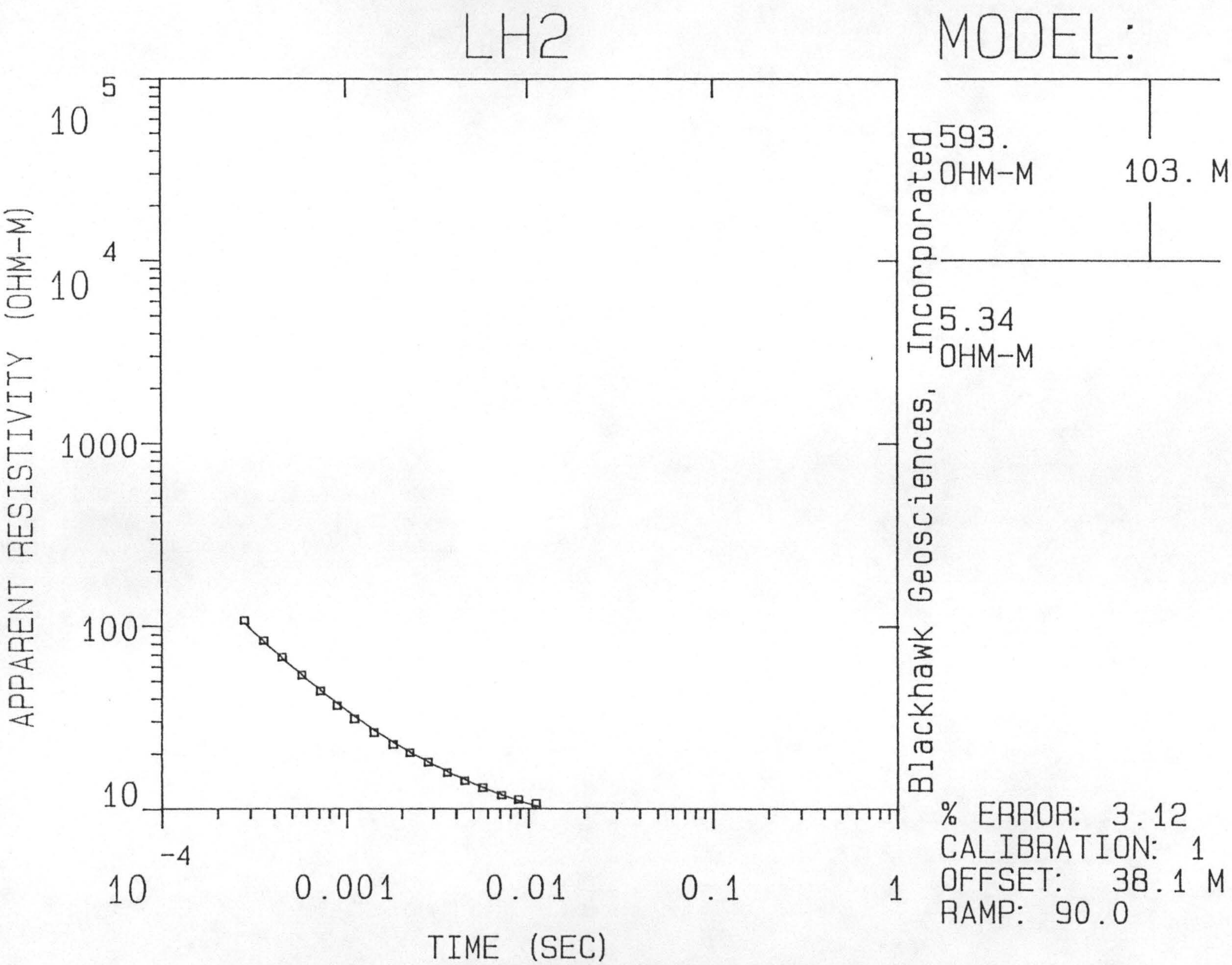
	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	2.41E+02	2.38E+02	1.213	
2	1.10E-04	1.92E+02	1.93E+02	-0.936	
3	1.40E-04	1.51E+02	1.52E+02	-0.816	
4	1.77E-04	1.19E+02	1.20E+02	-1.002	
5	2.20E-04	9.65E+01	9.68E+01	-0.350	
6	2.80E-04	7.65E+01	7.69E+01	-0.477	
7	3.55E-04	6.19E+01	6.17E+01	0.261	
8	4.43E-04	5.13E+01	5.07E+01	1.060	
9	5.64E-04	4.18E+01	4.14E+01	1.027	
10	7.13E-04	3.48E+01	3.43E+01	1.405	
11	8.81E-04	2.91E+01	2.92E+01	-0.372	
12	1.10E-03	2.49E+01	2.50E+01	-0.353	
13	1.41E-03	2.11E+01	2.11E+01	0.093	
14	1.77E-03	1.80E+01	1.83E+01	-1.762	
15	2.20E-03	1.62E+01	1.61E+01	0.315	
16	2.80E-03	1.46E+01	1.42E+01	2.902	
17	3.55E-03	1.26E+01	1.26E+01	-0.087	
18	4.43E-03	1.14E+01	1.14E+01	0.061	
19	5.64E-03	1.01E+01	1.03E+01	-2.097	

R: 38. X: 0. Y: 38. DL: 76. REQ: 42. CF: 1.0000
CLHZ ARRAY, 19 DATA POINTS, RAMP: 50.0 MICROSEC, DATA: LH1
1109 003N 001E Z OPR XTL H 5 8+100
Ch.21 = 0.05 Ch.22 = 0.089 Ch.23 = 12.5 Ch.24 =
RMS LOG ERROR: 7.44E-03, ANTILOG YIELDS 1.7272 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.99		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1



LH2
MODEL:
593.
OHM-M
103. M
5.34
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^{-4}
0.001
0.01
0.1
1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 3.12
CALIBRATION: 1
OFFSET: 38.1 M
RAMP: 90.0

LH2

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		97.5	320.0		
593.39	102.7	-5.1	-16.8	0.2	0.2
5.34					

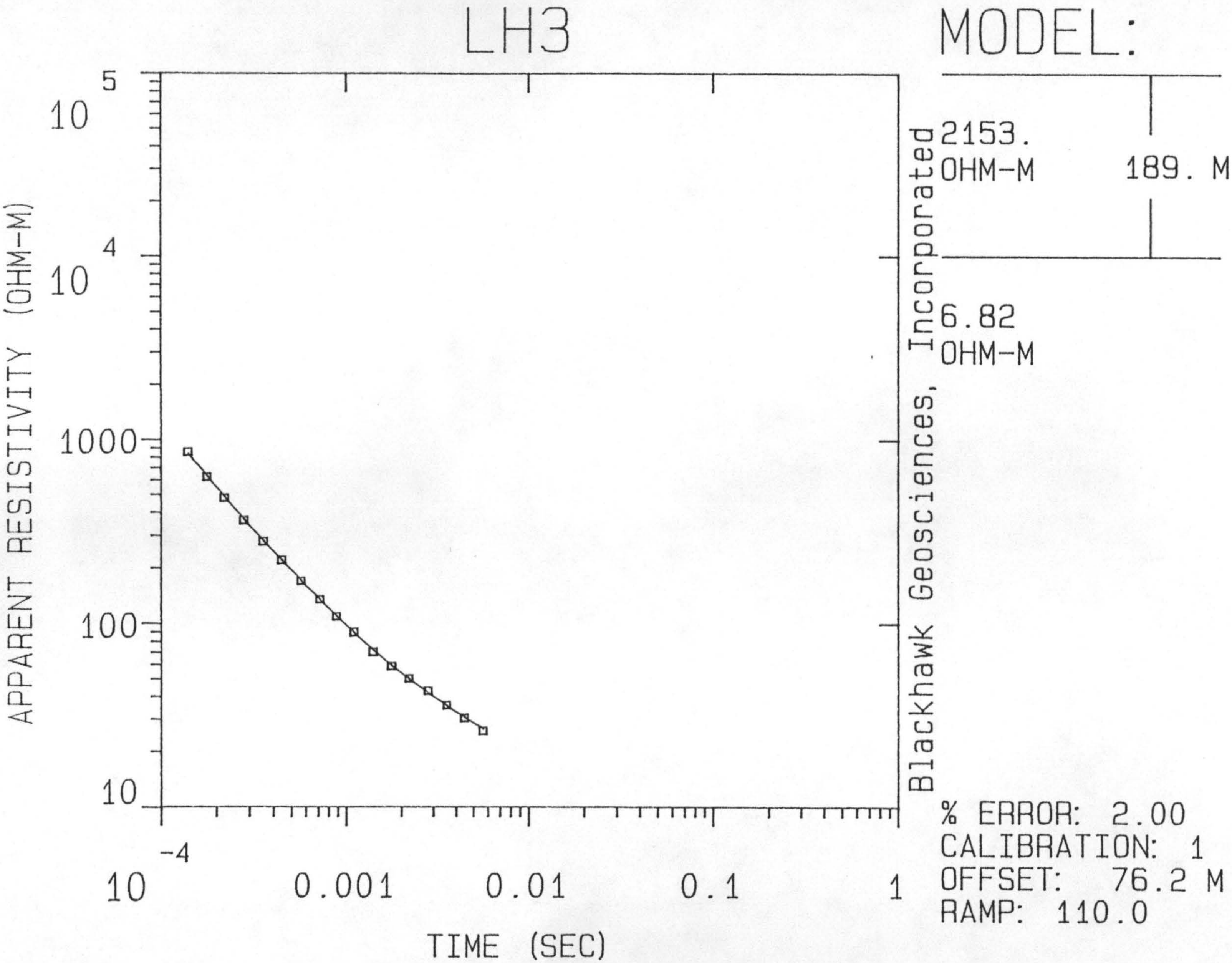
	TIMES	DATA	CALC	% ERROR	STD ERR
1	2.80E-04	1.07E+02	1.04E+02	3.679	
2	3.55E-04	8.36E+01	8.21E+01	1.809	
3	4.43E-04	6.81E+01	6.68E+01	1.976	
4	5.64E-04	5.41E+01	5.39E+01	0.309	
5	7.13E-04	4.41E+01	4.44E+01	-0.519	
6	8.81E-04	3.66E+01	3.76E+01	-2.579	
7	1.10E-03	3.10E+01	3.20E+01	-3.121	
8	1.41E-03	2.62E+01	2.69E+01	-2.705	
9	1.80E-03	2.25E+01	2.31E+01	-2.424	
10	2.22E-03	2.02E+01	2.03E+01	-0.563	
11	2.80E-03	1.80E+01	1.79E+01	0.263	
12	3.55E-03	1.58E+01	1.59E+01	-0.898	
13	4.43E-03	1.43E+01	1.44E+01	-0.892	
14	5.64E-03	1.30E+01	1.30E+01	0.290	
15	7.13E-03	1.19E+01	1.19E+01	0.069	
16	8.81E-03	1.13E+01	1.11E+01	1.772	
17	1.10E-02	1.07E+01	1.03E+01	4.007	

R: 38. X: 0. Y: 38. DL: 76. REQ: 42. CF: 1.0000
CLHZ ARRAY, 17 DATA POINTS, RAMP: 90.0 MICROSEC, DATA: LH2
1109 003N 002E Z OPR XTL H 4 8+100
Ch.21 = 0.09 Ch.22 = 0.089 Ch.23 = 23.5 Ch.24 =
RMS LOG ERROR: 1.34E-02, ANTILOG YIELDS 3.1239 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.01		
P 2	-0.01	0.99	
T 1	0.01	0.00	1.00
	P 1	P 2	T 1



LH3
MODEL:
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-4
0.001
0.01
0.1
1
TIME (SEC)
2153.
OHM-M
189. M
6.82
OHM-M
Blackhawk Geosciences, Incorporated
% ERROR: 2.00
CALIBRATION: 1
OFFSET: 76.2 M
RAMP: 110.0

LH3

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		175.3	575.0		
2152.64	189.1	-13.8	-45.3	0.1	0.1
6.82					

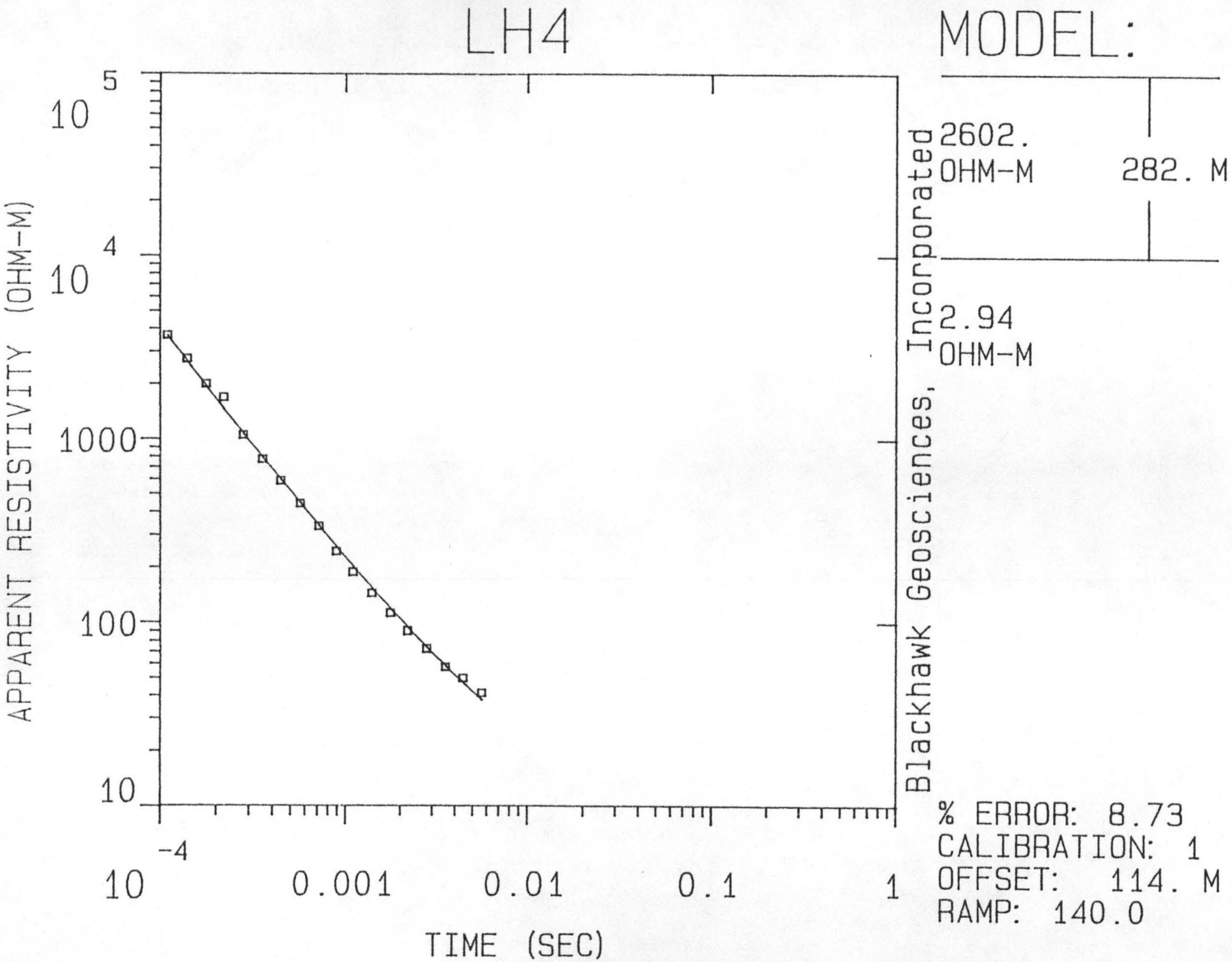
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.40E-04	8.55E+02	8.38E+02	2.002	
2	1.77E-04	6.24E+02	6.28E+02	-0.647	
3	2.20E-04	4.79E+02	4.83E+02	-0.988	
4	2.80E-04	3.62E+02	3.65E+02	-0.825	
5	3.55E-04	2.78E+02	2.79E+02	-0.313	
6	4.43E-04	2.20E+02	2.19E+02	0.349	
7	5.64E-04	1.69E+02	1.70E+02	-0.291	
8	7.13E-04	1.35E+02	1.34E+02	0.652	
9	8.81E-04	1.09E+02	1.09E+02	-0.139	
10	1.10E-03	8.96E+01	8.91E+01	0.484	
11	1.40E-03	7.03E+01	7.18E+01	-2.151	
12	1.77E-03	5.88E+01	5.91E+01	-0.512	
13	2.20E-03	5.02E+01	4.98E+01	0.874	
14	2.80E-03	4.30E+01	4.17E+01	3.168	
15	3.55E-03	3.59E+01	3.54E+01	1.359	
16	4.43E-03	3.05E+01	3.07E+01	-0.626	
17	5.64E-03	2.60E+01	2.66E+01	-2.184	

R: 76. X: 0. Y: 76. DL: 152. REQ: 84. CF: 1.0000
CLHZ ARRAY, 17 DATA POINTS, RAMP: 110.0 MICROSEC, DATA: LH3
1109 003N 003E Z OPR XTL H 4 8+100
Ch.21 = 0.11 Ch.22 = 0.089 Ch.23 = 19 Ch.24 = 2
RMS LOG ERROR: 8.59E-03, ANTILOG YIELDS 1.9981 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.31		
P 2	-0.02	1.00	
T 1	0.01	0.00	1.00
	P 1	P 2	T 1



LH4
MODEL:
2602.
OHM-M
282. M
2.94
OHM-M
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-4
0.001
0.01
0.1
1
TIME (SEC)
Blackhawk Geosciences, Incorporated
% ERROR: 8.73
CALIBRATION: 1
OFFSET: 114. M
RAMP: 140.0

LH4

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		263.7	865.0		
2601.73	282.5	-18.8	-61.8	0.1	0.1
2.94					

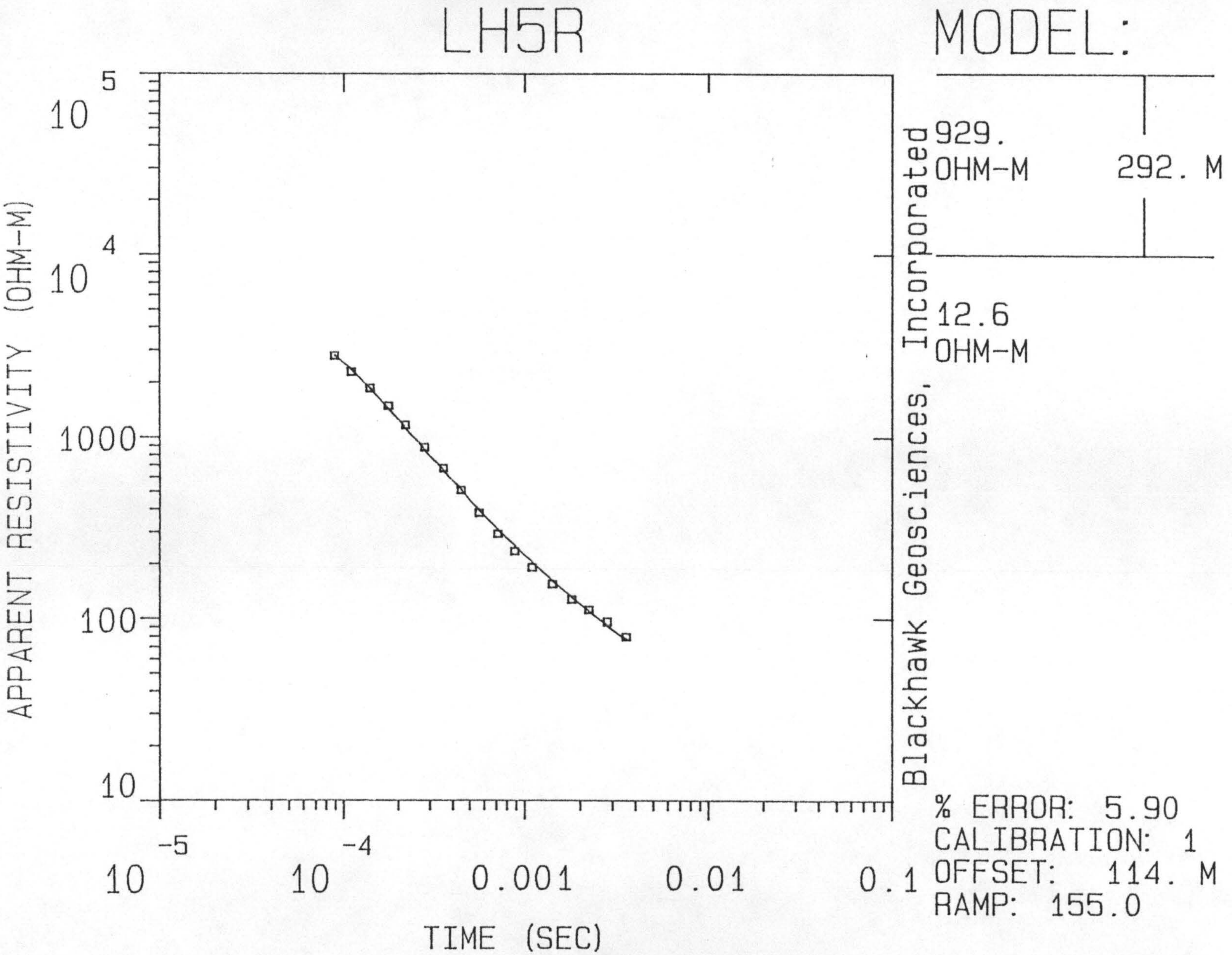
	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	3.67E+03	3.65E+03	0.682	
2	1.40E-04	2.74E+03	2.64E+03	3.901	
3	1.77E-04	2.00E+03	1.93E+03	3.535	
4	2.20E-04	1.68E+03	1.45E+03	16.050	
5	2.80E-04	1.05E+03	1.06E+03	-1.513	
6	3.55E-04	7.70E+02	7.86E+02	-2.040	
7	4.43E-04	5.86E+02	5.96E+02	-1.715	
8	5.64E-04	4.42E+02	4.43E+02	-0.336	
9	7.13E-04	3.34E+02	3.34E+02	-0.247	
10	8.90E-04	2.43E+02	2.58E+02	-5.600	
11	1.10E-03	1.88E+02	2.02E+02	-6.951	
12	1.40E-03	1.44E+02	1.54E+02	-6.101	
13	1.77E-03	1.13E+02	1.19E+02	-5.343	
14	2.20E-03	9.01E+01	9.43E+01	-4.548	
15	2.80E-03	7.26E+01	7.36E+01	-1.325	
16	3.55E-03	5.77E+01	5.82E+01	-0.827	
17	4.43E-03	5.01E+01	4.71E+01	6.302	
18	5.64E-03	4.15E+01	3.78E+01	9.718	

R: 114. X: 0. Y: 114. DL: 229. REQ: 127. CF: 1.0000
CLHZ ARRAY, 18 DATA POINTS, RAMP: 140.0 MICROSEC, DATA: LH4
1209 003N 004E Z OPR XTL L 6 10+100
Ch.21 = 0.14 Ch.22 = 0.89 Ch.23 = 19 Ch.24 = 52
RMS LOG ERROR: 3.64E-02, ANTILOG YIELDS 8.7336 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.05		
P 2	-0.09	0.84	
T 1	0.00	-0.01	1.00
	P 1	P 2	T 1



LH5R
APPARENT RESISTIVITY (OHM-M)
10^5
10^4
1000
100
10
10^-5
10^-4
0.001
0.01
0.1
TIME (SEC)
Blackhawk Geosciences, Incorporated
MODEL:
929.
OHM-M
292. M
12.6
OHM-M
% ERROR: 5.90
CALIBRATION: 1
OFFSET: 114. M
RAMP: 155.0

LH5R

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		326.1	1070.0		
929.34	292.3	33.8	110.9	0.3	0.3
12.56					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	8.90E-05	2.77E+03	2.80E+03	-0.753	
2	1.10E-04	2.28E+03	2.33E+03	-2.516	
3	1.40E-04	1.85E+03	1.84E+03	0.974	
4	1.77E-04	1.48E+03	1.42E+03	4.292	
5	2.20E-04	1.16E+03	1.11E+03	4.901	
6	2.80E-04	8.78E+02	8.45E+02	3.993	
7	3.55E-04	6.69E+02	6.47E+02	3.308	
8	4.43E-04	5.08E+02	5.08E+02	-0.054	
9	5.64E-04	3.81E+02	3.93E+02	-2.866	
10	7.13E-04	2.93E+02	3.08E+02	-4.854	
11	8.81E-04	2.35E+02	2.50E+02	-6.074	
12	1.10E-03	1.91E+02	2.03E+02	-5.509	
13	1.41E-03	1.55E+02	1.61E+02	-3.734	
14	1.80E-03	1.28E+02	1.30E+02	-1.815	
15	2.22E-03	1.12E+02	1.09E+02	2.409	
16	2.80E-03	9.62E+01	9.12E+01	5.497	
17	3.55E-03	7.99E+01	7.67E+01	4.214	

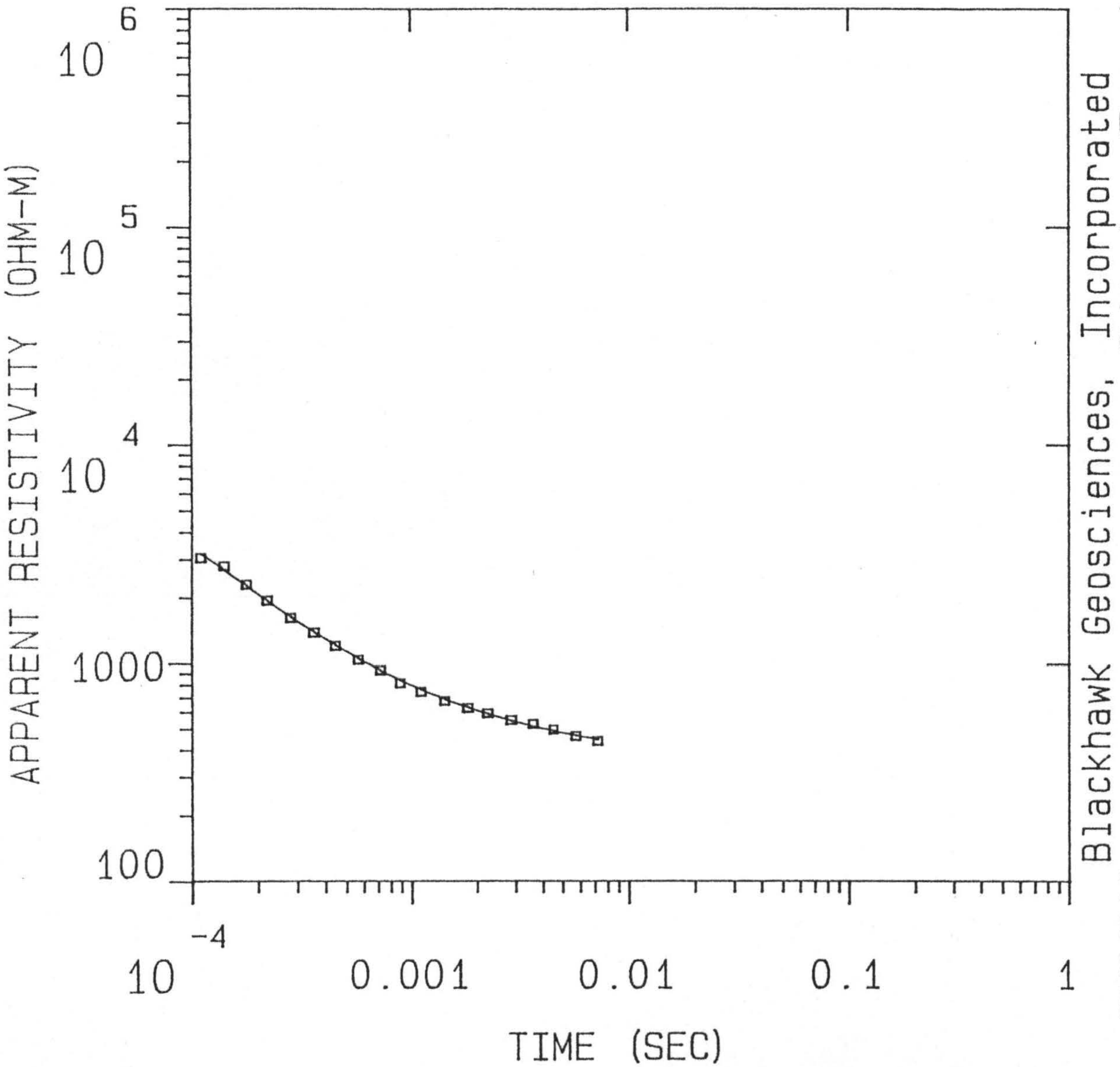
R: 114. X: 0. Y: 114. DL: 229. REQ: 127. CF: 1.0000
CLHZ ARRAY, 17 DATA POINTS, RAMP: 155.0 MICROSEC, DATA: LH5R
1209 003N 005E Z OPR XTL H 5 8+100
Ch.21 = 0.155 Ch.22 = 0.089 Ch.23 = 19 Ch.24 =
RMS LOG ERROR: 2.49E-02, ANTILOG YIELDS 5.8994 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

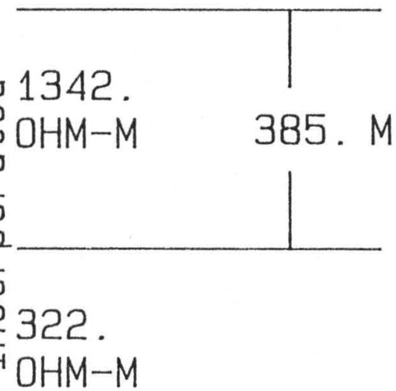
PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	0.95		
P 2	-0.03	0.93	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

LH6R



MODEL:



% ERROR: 2.93
CALIBRATION: 1
OFFSET: 229. M
RAMP: 210.0

LH6R

MODEL: 2 LAYERS

RESISTIVITY (OHM-M)	THICKNESS (M)	ELEVATION (M)	ELEVATION (FEET)	CONDUCTANCE (S) LAYER	CONDUCTANCE (S) TOTAL
		524.3	1720.0		
1341.87	384.7	139.5	457.7	0.3	0.3
322.19					

	TIMES	DATA	CALC	% ERROR	STD ERR
1	1.10E-04	3.05E+03	3.19E+03	-4.334	
2	1.40E-04	2.79E+03	2.67E+03	4.286	
3	1.77E-04	2.30E+03	2.25E+03	2.029	
4	2.20E-04	1.95E+03	1.92E+03	1.140	
5	2.80E-04	1.62E+03	1.62E+03	-0.303	
6	3.55E-04	1.39E+03	1.39E+03	-0.113	
7	4.43E-04	1.21E+03	1.21E+03	-0.216	
8	5.64E-04	1.04E+03	1.05E+03	-0.893	
9	7.13E-04	9.33E+02	9.27E+02	0.687	
10	8.81E-04	8.15E+02	8.36E+02	-2.510	
11	1.10E-03	7.44E+02	7.58E+02	-1.965	
12	1.41E-03	6.76E+02	6.85E+02	-1.276	
13	1.80E-03	6.27E+02	6.28E+02	-0.235	
14	2.22E-03	5.92E+02	5.86E+02	0.939	
15	2.85E-03	5.50E+02	5.46E+02	0.807	
16	3.60E-03	5.29E+02	5.14E+02	2.808	
17	4.49E-03	4.97E+02	4.89E+02	1.612	
18	5.70E-03	4.64E+02	4.66E+02	-0.411	
19	7.19E-03	4.40E+02	4.47E+02	-1.473	

R: 229. X: 0. Y: 229. DL: 457. REQ: 254. CF: 1.0000
CLHZ ARRAY, 19 DATA POINTS, RAMP: 210.0 MICROSEC, DATA: LH6R
1309 003N 006E Z OPR XTL H 5 8+100
Ch.21 = 0.21 Ch.22 = 0.089 Ch.23 = 14 Ch.24 = 2
RMS LOG ERROR: 1.25E-02, ANTILOG YIELDS 2.9255 %
LATE TIME PARAMETERS

* Blackhawk Geosciences, Incorporated *

PARAMETER RESOLUTION MATRIX:
"F" MEANS FIXED PARAMETER

P 1	1.00		
P 2	0.00	1.00	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1